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# A New Energy Harvesting Design Concept: Multimodal Energy Harvesting Skin

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**This paper proposes an advanced design concept for a piezoelectric energy harvesting (EH) device, multimodal EH skin structure, a thin and compact harvester which can generate power from multimodal vibration. Multimodal EH skin is an extended study of our previous works, EH skin, which is a new conceptual design for piezoelectric energy harvester by combining a vibrating skin structure and an additional thin piezoelectric layer into one embodiment. A computational (FE) model for the EH skin's multilayers – a vibrating skin structure and a piezoelectric layer – is constructed and the optimal topology and shape of the piezoelectric layer is found for maximum power generation from multiple vibration modes. For finding topological distribution, the piezoelectric material is segmented along inflection lines from multiple vibration modes of interests in order to minimize voltage cancellation. A case study taken from an outdoor unit skin proves the excellent performance of multimodal EH skin by showing larger power generation rather than an EH skin without segmentation or a unimodal EH skin. The presented design concept can be easily applied to any engineering system with harmonic-vibrating skins.**

## Nomenclature

| | | |
|---|---|---|
| $A_f$ | = | harmonic excitation amplitude |
| $f^e_k$ | = | $k$th excitation frequency |
| $f^r_i$ | = | natural frequency of $i$th mode |
| $\phi_V$ | = | phase angle of voltage |
| $I$ | = | electric current |
| $P$ | = | electric power |
| $R_j$ | = | external resistor for $j$th segment |
| $V$ | = | voltage |

## Introduction

THE researches on energy harvesting (EH) have aimed to construct self-powered electrical devices (e.g., global positioning systems, wireless sensors) by using ambient, otherwise wasted, energy. A plenty of researches have been done in this research area for last two decades so that the current state-of-art could generate electrical power for wireless sensor nodes and small electronics[1-3]. This EH technology is highly demanding; wireless sensors are increasingly used in the areas of PHM and building automation, and batteries can be troublesome due to their shortcomings such as limited lifespan and replacement cost (\$80~\$500 including labor[4]) especially when sensors are installed remotely. This issue has motivated the rapid growth of the EH field.

Vibration is one of the most available ambient energy forms found in civil structures, machines, human body, and so on. For vibration energy conversion into electrical energy, piezoelectricity is known as the most efficient energy conversion principle[4-8]. Among the commercially available piezoelectric material such as PZT(Lead zirconate titanate), ZnO (Zinc oxide), PVDF (Polyvinylidene Difluoride), PZT is reported to possess the best conversion efficiency among them[5].

Most piezoelectric EH devices take a form of cantilever with a tip mass. Even though their successful energy conversion case studies utilizing ambient vibration have been reported[8-10], some drawbacks have been discovered from a practical point of view. First, the cantilever EH device requires an extra space because of a bulky proof mass

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and additional clamping part. Second, the cantilever EH device must be protected from dirt, moisture, and other environmental harms; the cantilever EH device should be kept inside housing for the protection. Third, and most importantly, a great deal of vibration energy can be lost due to the loosened clamping on a vibration source.

The disadvantages of the cantilever design motivate the proposition of a new EH design concept entitled “energy harvesting (EH) skin.” In the EH skin, thin piezoelectric patches are directly attached onto a vibrating shell structure to implement compact and energy-efficient design. The direct attachment of thin piezoelectric patches is the well-known method for vibration control[11, 12] and nondestructive structural health monitoring[13, 14]. However, there has been no systematic design approach to use direct attachment as an energy harvester and determine the optimal piezoelectric material layout for maximum power generation. Considering the multi-harmonic vibration characteristic of most engineering systems (e.g., airplane wing, railroad train, AC unit), this paper proposes a systematic design guideline on the multimodal EH skin which utilizes multiple harmonics vibration for larger power generation.

## I. Introduction to Case Study: Outdoor Unit

This case study employed a cooler condensing unit which was found in the University of Maryland campus (Figure 1). Condensing units are excellent ambient vibration structures for EH: they are easily found around buildings and have relatively high vibration amplitude. The unit is excited by internal rotating actuator (motor) with fixed frequency.

The energy harvester will be configured on the top plate of the unit (steel, 1.12 m × 0.86 m × 3mm). The top plate is assembled with lower body with 8 bolts (as shown in Figure 1) through which the motor vibration is transferred. The vibration data is thus measured at 8 bolts for input loading condition in the simulation (see the next chapter). Figure 2 shows the measured vibration data from one of the 8 joints. Time domain vibration data is acquired and transformed into frequency domain using Fast Fourier Transformation (FFT). The FFT plot in Figure 2 shows a typical "harmonic" vibration: multiple peaks (harmonic series) are observed at $k \times f^e_1$ where $k$ is natural number and $f^e_1$ is the fundamental frequency (29.3Hz in this case). This vibration characteristic indicates that higher power can be generated if the vibration from multiple frequencies are harvested. For optimal locations and shapes of the piezoelectric patches in multimodal EH skin, a systematic design guideline is devised in the next chapter.

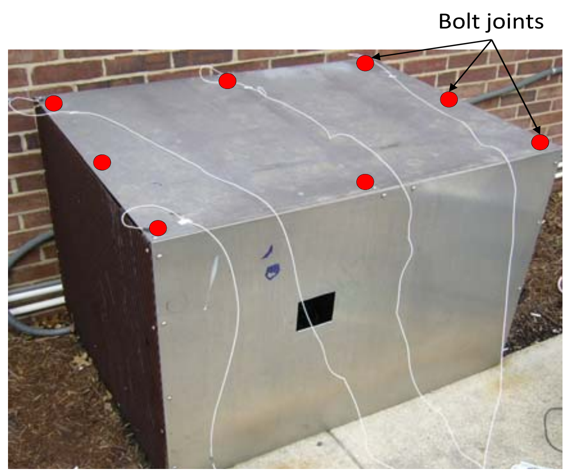



**Figure 1. Outdoor Unit.**

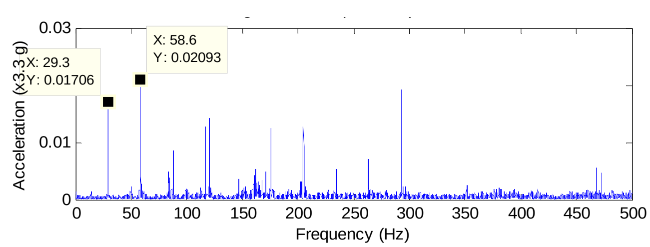



**Figure 2. Harmonics in Frequency Domain.**

## II. Design Principle for Multimode EH Skin

### A. Layer configuration of EH Skin

Unlike a cantilever type piezoelectric unimorph/bimorph, EH skin is implemented simply by directly attaching thin piezoelectric patches onto the vibrating skin. The vibrating skin takes a role of substrate. PZT patches are attached on the top or bottom surface of the substrate, or even both surfaces. This conceptual design enables an EH device without additional fixture and protecting cover (once they are attached inside the vibrating structure). Figure 3 shows the FE model for EH skin where PZT patches (1 mm thick) are attached on both surfaces to form a bimorph cross-section. The PZT patches and substrate are modeled using SOLID5 and SOLID45 element in ANSYS, respectively. SOLID5 element is a 3D coupled-field solid element which has 4 DOFs (degrees of freedom) at each node: 3 translational DOFs and volt. Totally 56×44×3 number of finite elements are used for modeling. The volt DOFs on the outer surfaces on PZT are coupled to represent electrodes, and those on the interface with substrate are

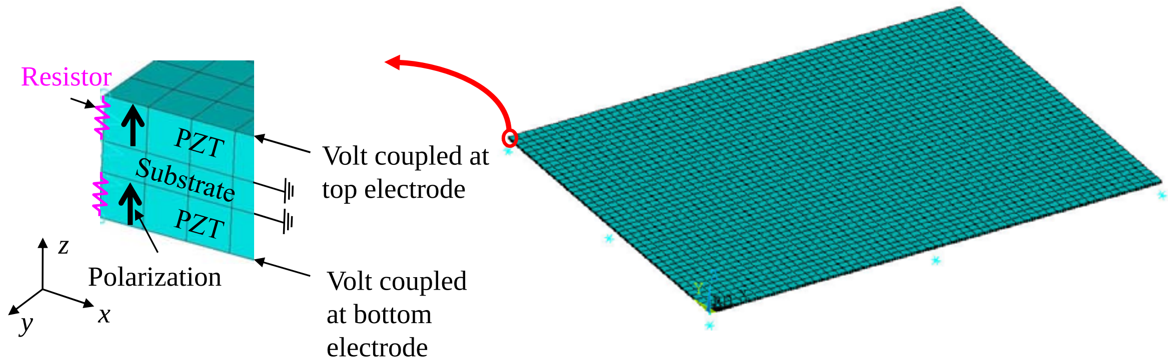



**Figure 3. FE modeling of EH skin.** *PZT thickness is exaggerated for better understanding.*

grounded, as shown in Figure 3. CIRCU94 element is used to represent an external resistor where the power is obtained.

Two kinds of FE analysis have been performed to understand the vibration behavior of the skin: modal and harmonic analysis. In modal analysis all degrees of freedom at 8 bolting joints are fixed. The modal analysis results are shown in Figure 4 where the first ten vibration modes are displayed. The first mode shape is fundamental up-and-down vibration, and the shapes become more complex as the mode number increases. In harmonic analysis vertical (*z* direction in Figure 3) excitation conditions (amplitude $A_f$ = 0.2g) are identically assigned at 8 bolting joints with the first two harmonic frequencies in Figure 2 (29.3 and 59.6 Hz). In the harmonic analysis the symmetric vibration responses are obtained for each excitation frequency: the response is very similar to the 1st and 5th mode shapes in Figure 4. In this research, therefore, EH skin is designed considering 1st and 5th vibration modes.

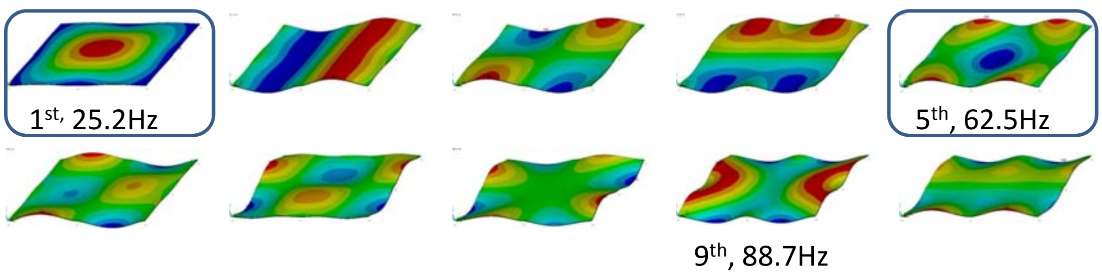



**Figure 4. First 10 modal shapes.**

## B. Inflection Line Elimination

The design strategy for efficient power generation from multiple harmonic vibration modes are explained in this section. If the whole area of substrate of the EH skin is covered with PZT material, the power is not generated at maximum efficiency due to the cancellation effect[15-17]. The cancellation effect refers to the voltage cancellation due to different strain signs in one PZT material. Figure 5 shows an example of this effect from the second vibration mode of a cantilever. In this mode the voltage cancellation is occurred

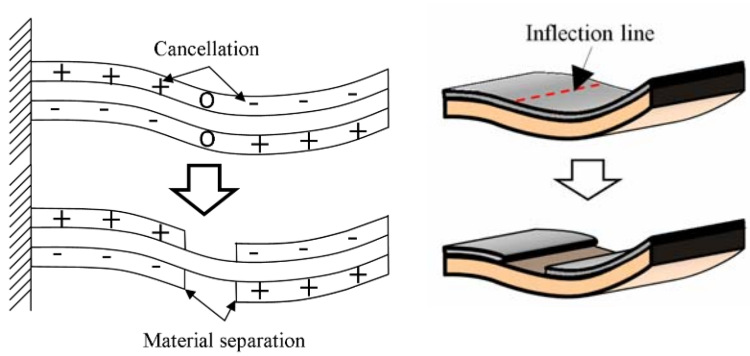


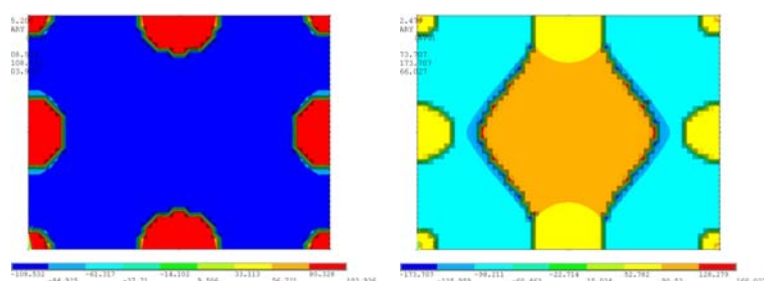

**Figure 5. Cancellation minimization by eliminating inflection line.**

when the sign of mode-shape curvature changes. Obviously this effect can be minimized by eliminating material around inflection line as shown at the bottom of Figure 5. In this research, 3 design candidates are compared considering the inflection lines of the following modes: the 1st mode, 5th mode, or even both modes.

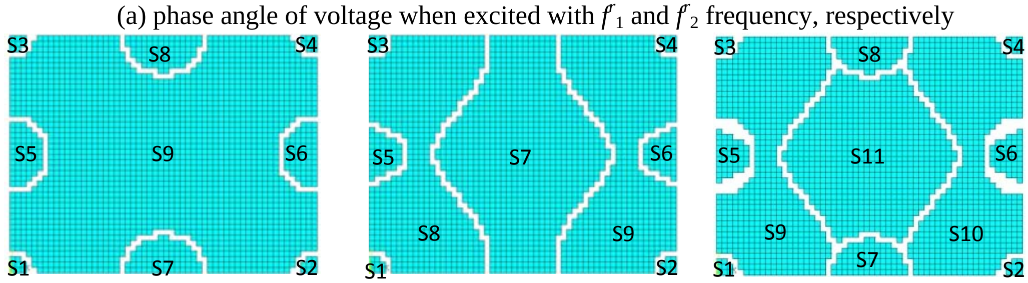
The following procedure summarizes how to detect inflection lines and eliminate them:

- Step 1: Erase external resistors and the volt DOF coupling condition for both top and bottom electrodes.
- Step 2: Perform modal analysis to find the resonant frequency ($f^r_1$ and $f^r_2$) of the skin structure.
- Step 3: Perform harmonic analysis for each resonant frequency: the amplitudes ($A_f$) and phase angles are all identical at 8 bolting joints.
- Step 4: For each excitation frequency, extract the volt phase angle ($\phi_V$) from each node at top and bottom electrode level.
- Step 5: Extract node set from PZT elements where steep change of $\phi_V$ is detected.
- Step 6: Find elements which include the node sets found in Step 4 and eliminate them.

Figure 6(a) shows phase angle plots ($\phi_V$) for $f^r_1$ and $f^r_2$ frequency excitation. Each design has different PZT material layout which causes slight difference on resonant peak location. So the power comparison on the fixed excitation frequency may lead incorrect conclusion. To prevent this, we compare the performance of each EH skin when it is excited at the resonant frequency. The damping ratio is assumed as 2%. In both excitation cases the domain is clearly segmented. In $f^r_1$ excitation case, the vicinity of each bolting joint has positive phase while the other region (including the center of plate) has negative phase. The phase difference is about 180°. In $f^r_2$ excitation case, the division by phase angle is similar along two lateral sides, but a larger vertical sub-domain is detected through the center. The first two figures in Figure 6(b) show the PZT layer segmentation according to the phase response of $f^r_1$ and $f^r_2$ excitation (Case 1 and 2). Case 3 is additionally considered where the inflection lines from both Case 1 and 2 are eliminated, which is named as multimodal EH skin. For each case the PZT layers are divided into multiple segments and they are numbered as shown in Figure 6(b). For each segment, an external resistor is connected between the two electrodes (as shown in the left figure of Figure 3).



(a) phase angle of voltage when excited with $f^r_1$ and $f^r_2$ frequency, respectively




(b) PZT segmentation cases (Case 1, 2, and 3)

**Figure 6. Cancellation minimization by eliminating inflection line.**

### C. Power Generation with Optimal External Resistance

For exact power evaluation the optimal value of each external resistor value ($R$) should be found. The larger $R$ may yield the larger voltage ($V$), but smaller current ($I$) at the same time because the circuit approaches to open circuit status as $R\rightarrow\infty$. The electric power ($P$), calculated as $P=VI/2$ (RMS measure), reaches its maximum at certain

*R* value (optimal *R*, or *R**). *R** values are found (for each segment) by solving the optimization problem for the maximization of the power sum as follows:

**Table 1. Power generation of EH skin**

| | | Case 0 | Case 1 | Case 2 | Case 3 (multimodal EH skin) |
|---|---|---|---|---|---|
| Power(mW) | $f^r_1$ excitation | 723 | 784 | 774 | 819 |
| | $f^r_2$ excitation | 1.60 | 61.0 | 86.4 | 86.1 |
| | Sum | 724.6 | 845.0 | 860.4 | 905.1 |

$$Max \quad \sum_i \sum_j P_j(R_j) \tag{1}$$

where $P_j$ is the power obtained from segment $j$ (throught $R_j$), and $i$ is the index for excitation mode ($i$=1 for $f^r_1$ excitation and $i$=2 for $f^r_2$ excitation). This optimization is performed for each segmentation case (see Figure 6(b)). Power generation results are summarized in Table 1. To prove the importance of segmentation, the harvester without segmentation (Case 0) is additionally considered. Among the first three cases (Case 0 to 2), Case 0 produces the minimum power. Each segmented design (Case 1 and 2) generates the maximum power at each corresponding mode shape: Case 1 (mode 1 considered) produces the largest power (784mW) for $f^r_1$ excitation, and Case 2 (mode 5 considered) does (86.4mW) for $f^r_5$ excitation .The power sum in the last row shows about 17% and 19% power increase when Case 1 and 2 is compared with Case 0, proving the value of segmented design.

More importantly, we can verify the excellent power generation capability of multimodal EH skin (Case 3). It shows the best performance out of all the four design cases: 25% increase compared to Case 0. This fact verifies that the elimination of inflection lines from multiple vibration modes ensures the larger power generation.

## III. Conclusion

A new EH harvesting design concept, multimodal EH skin, was proposed for power generation from multiple harmonic vibration modes. To minimize voltage cancellation, piezoelectric patches are segmented based on the voltage phase angle. Two major findings are reported in this study: (i) the segmented EH skin showed larger power generation than the case without segmentation, and (ii) excellent power generating performance of multimodal EH skin - removal of inflection lines from multiple modes presented larger power under multiple harmonic excitation condition. This simple but capable design principle can be successfully applied to plenty of engineering systems which have thin vibrating skins. In the near future we plan to prove the versatility of the design concept with applications to various health monitoring and building automation where the power of wireless sensor network is supplied by the multimodal EH skin.

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