1. Introduction

The advances in wireless communications and low-power technology promote the use of wireless sensors. However, the limited life expectancy and high replacement cost of batteries make it difficult to use wireless sensors, although they have lots of benefits more than wired sensors. Energy harvesting (EH) technology, which scavenges electric power from ambient, otherwise wasted, energy sources, has been explored to develop self-powered wireless sensors and possibly eliminate battery replacement cost for wireless sensors. Among ambient energy sources, vibration energy, widely available, can be converted into electric power using a piezoelectric energy harvester that can generate alternating current in response to applied mechanical strain (S. R. Anton, 2007).

Even though piezoelectric energy harvesters have primarily designed as a cantilever beam, they have some practical drawbacks from a practical point of view: (a) an additional space required for a proof mass and clamping device, (b) a great deal of vibration energy loss when clamping conditions become loosened after long time use, (c) a fatigue failure expected due to excessive strains at a clamping part. As a compact and durable design concept, piezoelectric energy harvesting skin (EH skin) has been proposed to scavenge electric power from vibration energy of an engineered system with an additional thin piezoelectric layer as one embodiment (S. Lee, 2011), as shown in Figure 1.

It is of great importance to exploit rigorous theories and mechanics for developing piezoelectric EH skin. Therefore, this article presents important aspects of piezoelectric EH skin. The following sections will explain core technologies such as analysis, design, and demonstration of piezoelectric EH skin for successfully utilizing self-powered wireless sensors.

2. Analysis of Piezoelectric Energy Harvesting Skin

For the purpose of designing piezoelectric EH skin and selecting best sites for installation, it is important to preliminarily quantify harvestable electric power under a given vibration condition. This section discusses how to analyze piezoelectric EH skin with high-fidelity predictive capability.
2.1 Piezoelectric effect

The prefix ‘piezo’ comes from the Greek ‘piezein’ which means to pressure or squeeze. Electricity is a physical phenomenon related to the flow of an electric charge. Therefore, piezoelectricity is an interaction between electrical and mechanical behaviors. As a direct piezoelectric effect, a piezoelectric material can produce electric polarization due to applied mechanical strain, as shown in Figure 2. Piezoelectric energy harvesting and piezoelectric transducers correspond to this direct piezoelectric effect. The amount of voltage generated is proportional to dynamic strain. Conversely, when electric polarization is applied, a piezoelectric material becomes strained. This is called the inverse piezoelectric effect.

2.2 Electromechanically-Coupled Analytical Model of Piezoelectric Energy Harvesting Skin

An electromechanically-coupled analytical model which describes relationships among variables of piezoelectric EH skin can be implemented to understand the first principle of energy conversion. Furthermore, the electromechanically-coupled analytical model not only enables quick quantification of the harvestable electric power but also helps provide information about important design considerations. In most cases, it is desirable to conduct this analytical approach prior to computational or experimental one. Since the analytical model can be considered as a set of mathematical equations (e.g., the governing equations, constitutive equations, geometry, loading conditions, and boundary conditions) needed to

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Table 1 Modeling approaches for developing the electromechanically-coupled analytical model of piezoelectric energy harvesting skin

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<th>Physics of interest</th>
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describe physics reality, their modeling approach should be carefully employed to enhance the predictive capability of the analytical model. Table 1 summarizes the modeling approaches for developing the electromechanically-coupled analytical model of piezoelectric EH skin.

The overall procedure for developing the electromechanically-coupled analytical model of piezoelectric EH skin is as follows. First, the Hamilton’s principle is used to derive the differential equations of motion based on the Kirchhoff plate theory. Because the piezoelectric patches are generally manufactured as a thin plate, piezoelectric EH skin can be modeled as the two-dimensional Kirchhoff plate which is analogue to the one-dimensional Euler-Bernoulli beam. Second, the free vibration analysis is performed to solve the undamped natural frequencies and the corresponding mode shapes for a given boundary condition. However, due to the geometric non-homogeneity of piezoelectric EH skin, such as the discontinuity at the left and right ends of the segmented piezoelectric patches, it is tedious to find the exact solution. Therefore, the Rayleigh-Ritz method, which is one of series discretization technique for approximating a distributed-parameter system, is implemented to perform the free vibration analysis of piezoelectric EH skin. Third, the electrical circuit equation is derived by substituting the piezoelectric constitutive relation into the Gauss’s law. As the last step, the frequency response for the output voltage generated by one piezoelectric patch is obtained by solving the differential equations of motion and electrical circuit equation simultaneously.

Because the electromechanically-coupled analytical model is developed based on the Kirchhoff plate theory, can take account of the effect of the two-dimensional bending behaviors (e.g., two normal strains, the Poisson’s ratio, and the aspect ratio) on the amount of harvestable electric voltage.

2.3 Finite Element Model of Piezoelectric Energy Harvesting Skin

If the geometry of a vibrating engineered system or loading conditions are complex, it is better to perform multi-physics finite element (FE) simulation rather than analytical approach. The FE model can be developed by using ANSYS® commercial software, as shown in Figure 3.

The electrode layer and the adhesive material (e.g., conductive epoxy) are ignored in the FE model due to their extremely small thickness and a perfect bonding condition. The piezoelectric patches can be modeled using a SOLID5 element which has four coupled field degrees of freedom. Three degrees of freedom define the translational displacements (UX, UY, and UZ) based on the global coordinate system. The other degree of freedom indicates the electric potential difference (VOLT) between top and bottom electrodes. The substrate (surface of a vibrating engineered system) can be modeled by SOLID45 element with three translation DOFs.

The VOLT degree of freedom on the top surface of the piezoelectric patch is coupled to represent the top electrode, while that on the interface between the piezoelectric patch and the substrate is grounded (zero electric potential) to represent the bottom electrode. These two electrodes are connected with an external electrical load which is the resistance of the measurement equipment.

3. Design Methodology for Piezoelectric Energy Harvesting Skin

As shown in Figure 1, EH skin consists of piezoelectric patches (e.g., lead zirconate titanate, polyvinylidene fluoride) directly attached to one substrate (the surface of vibrating engineered systems) as one embodiment. In this case, we are faced with one question: where is the optimal placement that piezoelectric patches should be attached onto the substrate for generating higher electric power? This important consideration drives a segmentation design of piezoelectric patches of EH skin.
3.1 Analytical Approach for Segmentation Design

The design rationale for a segmentation of piezoelectric patches can be clearly understood using the strain mode shapes of EH skin. Figure 4 shows the 1st strain mode shapes of a rectangular plate for a fully simply-supported (SSSS) and a fully clamped (CCCC) boundary condition.

Assume that piezoelectric EH skin be positioned onto the $xy$-plane. Then the above strain mode shapes can be obtained by the sum of the normal strain components $\epsilon_{xx}$ and $\epsilon_{yy}$. When the curvature of the transverse displacement of piezoelectric EH skin is positive, the output voltage is positive, and vice versa. No output voltage is generated when the sum of the normal strain components $\epsilon_{xx}$ and $\epsilon_{yy}$ is zero (i.e., inflection lines). This electromechanical phenomenon is called voltage cancellation. As shown in Figure 4, there is no inflection line in the 1st strain mode shape of a fully simply-supported rectangular plate, while inflection lines are developed in the fully clamped case.

For the purpose of avoiding voltage cancellation, the piezoelectric patch should be segmented along the inflection lines of the strain distribution, as shown in Figure 5. In the analytical approach, the Heaviside unit step function can represent the region covered with one segmented piezoelectric patch.

Therefore, it can be concluded from this observation that a segmentation design of piezoelectric patches depends on the strain mode shape, in other words, the given boundary condition of EH skin, as shown in Figure 6. Figure 6(a) shows no need of the piezoelectric patch segmentation, while Figure 6(b) shows five segmented piezoelectric patches for minimizing voltage cancellation. It can be confirmed from the strain mode shapes in Figure 4 that these segmentation designs are suitable for both cases.
3.2 Computational Approach for Segmentation Design

The computational methodology (see Figure 7) for segmentation design of piezoelectric EH skin includes two main subtasks: (i) topology optimization and (ii) shape optimization. In the topology optimization step, the design problem was defined to find the optimal distribution of the piezoelectric material subject to cost limitation. Based on the fact that the higher in-plane strain ensures the larger voltage generation when 31 mode is utilized, the topology optimization tries to eliminate the elements having low in-plane strain. The material distribution found in this step, however, may be difficult to fabricate at the laboratory level. Shape optimization is thus performed to fill the lack of manufacturability in the topology optimization step.

4. Experimental Demonstration for Operating Self-Powered Wireless Sensors

This section describes experimental demonstration which was performed with aim to check the feasibility of utilizing self-powered wireless sensors using piezoelectric EH skin.

4.1 Manufacturing Process of Piezoelectric Energy Harvesting Skin

The PZT which is a commercially available piezoelectric material can be used as the piezoelectric patch. The manufacturing process of piezoelectric EH skin is composed of five steps: (a) assigning PZT patches, (b) cutting, (c) bonding, (d) curing and (e) checking short circuitry as shown in Figure 8. First the PZT patches are assigned on the base structure for cutting. Next, the PZT patches are cut by a laser machine. For the machining process, the power level and speed of laser should be carefully determined to prevent brittle fracture of the PZT patches. In the bonding process, a conductive epoxy can be used to glue the segmented PZT patches on the base structure. After the attachment of the segmented PZT patches on the base structure, it should be cured for 15 minutes (70°C) in a hot chamber. The process is repeatedly done for all area of the base structure. Lastly, the short circuitry should be checked between the top and bottom.
4.2 Case I - Deterministic Harmonic Vibrations

Piezoelectric EH skin was demonstrated to produce electric energy from deterministic harmonic excitation (driving frequency = 50Hz, acceleration level = 1g). As shown in Figure 9(a), seven LEDs are light on when the base structure is vibrating. In addition, one wireless analog temperature sensor, transmitter, receiver, and the monitoring system (USB connection for the receiver to a personal computer) were used for demonstration, as shown in Figure 9(b). The temperature sensor node requires 5.3V for initiating and 2.7V for transmitting the acquired data. Furthermore, it requires about 15mW for continuous temperature monitoring. Therefore, it can be concluded from experimental observations that piezoelectric EH skin can scavenge enough electric power to operate seven LEDs and one temperature sensor node.

4.3 Case II - Random Vibrations from Actual Engineered System

In practice, most realistic vibrations of engineered systems have physical uncertainty such as the variation of amplitude and driving frequency. Thus it is of great importance to reliably scavenge electric power from random vibrations (H. J. Yoon, 2014). In this study, as an engineered system, an outdoor condensing unit of which a fan produces harmonic vibration is chosen for a feasibility study because similar
configuration of vibration can be found in many engineered systems (e.g., airplane wing, AC unit). It can be concluded from experimental observations that the amount of electric power generated by piezoelectric EH skin from the vibration energy of an outdoor condensing unit is sufficient to operate four wireless acceleration sensors and one wireless temperature sensor in real-time, as shown in Figure 10.

5. Conclusions

This article presented mechanics based analysis and design of piezoelectric EH skin. It can be concluded from demonstration that the amount of electric power generated by piezoelectric EH skin is sufficient to operate wireless sensors in real-time.

The future plan includes (a) the development of high-efficiency piezoelectric EH skin which may utilize multiple vibration modes, (b) reliability-based design optimization under physical uncertainty in the material properties and manufacturing tolerance, and (c) not a device-level but a system-level design by involving materials science, mechanical, and electrical engineering disciplines.

Reference