Reliability-Based Design Optimization for Energy Harvesting Skin Using a Plate Theory Based Analytical Model

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Abstract

Ambient vibration energy can be converted into electrical energy using a piezoelectric energy harvester which produces an electrical alternating current in response to mechanical strain. Even though most piezoelectric energy harvesters are cantilever-type, they have some drawbacks: 1) additional space is required due to proof mass and clamping part, 2) a great deal of vibration energy can be lost when clamping conditions become loosened after long time use. These practical disadvantages can be overcome by an energy harvesting skin (EH skin) which is directly attached on the surface of vibrating mechanical systems. As a basis of the EH skin design for improving the energy conversion efficiency, an analytical model should be developed to get physical insight and quantify harvestable electric power under a given vibration condition. Therefore, this study developed an electromechanically-coupled analytical model for the EH skin using the Kirchhoff plate theory. In a mechanical domain, the generalized Hamilton's principle was used to derive the governing differential equation of motion. A superposition method was employed to calculate the natural frequencies and mode shapes of thin rectangular plates which do not have at least one pair of opposite edges simply supported, since the Levy solution cannot directly handle it. In an electrical domain, the electrical circuit equation was derived by integrating the piezoelectric constitutive relation with the electric current output obtained from the Gauss law. The developed analytical model was used for two design rationales of the EH skin: 1) inflection lines extraction and 2) the reliability-based optimal locations and sizes of piezoelectric patches. First, the inflection lines of the dynamic strain distribution were extracted for piezoelectric material segmentation to avoid voltage cancellation. Second, the locations and sizes of the EH patches were found to reliably scavenge high electric power output. In uncertainty propagation, the known random variable, related with manufacturing tolerance, is thickness of the EH skin. On the other hand, the unknown random variables to be calibrated are piezoelectric strain coefficient, relative permittivity, and elastic modulus of piezoelectric layer and substrate layer. Several case studies demonstrate the effectiveness of the analytical model of the EH skin.

Keywords: EH Skin, Analytical Model, Levy Solution, Material Segmentation, Uncertainty Propagation

Acknowledgement: This work was partially supported by a grant from the Fusion Research Program for Green Technologies (0420-20120048) of National Research Foundation (NRF), funded by the Korean government's Ministry of Education, Science and Technology.