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에너지 하베스팅 스킨의 임피던스 정합을 위한 통합 설계 방법론

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Integrated Design Methodology for Impedance Matching of Energy Harvesting Skin

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1. Introduction

Advances in wireless communications and low-power technology have enabled more widespread use of wireless sensor networks(WSNs). However, the limited life expectancy and high replacement cost of batteries still make it difficult to use wireless sensors.[1] Piezoelectric energy harvesting (PEH) technology which harvests electrical energy from ambient vibration energy has emerged as a possible solution to eliminate the need for batteries in wireless sensors. Recently, as a compact and durable piezoelectric energy harvester, a PEH skin which can be directly attached onto a vibrating structure as one embodiment has been proposed. From a system integration perspective, one of the most important aspects is the impedance matching between the PEH skin and the electrical regulation. However, the impedance matching has been treated in the mechanical and electrical domains individually. Therefore, this work presents an integrated design methodology for impedance matching of a PEH skin by optimizing the mechanical and electrical design variables simultaneously to maximize electric power.

2. Design Methodology for Impedance Matching of PEH Skin

The several analytical models have been developed to predict electric power generated by a PZT patch attached to a substrate (see Fig. 1).

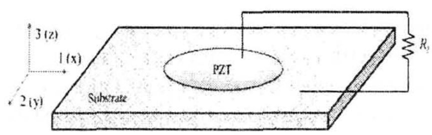

Fig. 1 A schematic representation of PEH skin

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According to IEEE Std. (1987), the linear constitutive equations for piezoelectric materials are given by equations (1) and (2).[2]

$$T_{ij} = c^{E}_{ijkl} - e_{kij} E_k \tag{1}$$

$$D_i = e_{ijk} S_{kl} + \varepsilon^{\prime}_{ik} E_k \tag{2}$$

where c^{E}_{ijkl}, e_{kij}, $\varepsilon^{\prime}_{ik}$ are the elastic, piezoelectric, and permittivity constants, respectively. T_{ij} is the mechanical stress, S_{kl} is the mechanical strain, D_{ij} is the electric displacement, and E_k is the electrical field. Because the thickness of the PEH skin is thin and the PZT patch is a transversely isotropic material, equation (2) can be reduced as:

$$D_3 = \bar{e}_{31}(S_1 + S_2) + \bar{\varepsilon}^{S}_{33} E_3 \tag{3}$$

where D_3 is the electric displacement component along the z-axis, $\bar{\varepsilon}^{\prime}_{33}$ is the permittivity component at constant strain. Because the electrodes of the PZT patch are connected to an external resistive load R_L, the electrical circuit equation can be expressed as:

$$\frac{d}{dt}\left(\oint(\bar{e}_{31}(S_1 + S_2) + \bar{\varepsilon}^{\prime}_{33}E_3)dA\right) = \frac{v(t)}{R_L} \tag{4}$$

where $v(t)$ denotes the output voltage under the given vibration condition. Equation (4) can be rewritten by assuming the uniform electric field in terms of the electric potential difference as:

$$\frac{dv(t)}{dt} + \frac{h_p v(t)}{R_L \bar{\varepsilon}^{\prime}_{33} A} = \frac{h_p \bar{e}_{31}}{\bar{\varepsilon}^{\prime}_{33} A}\oint \frac{\partial}{\partial t}(S_1 + S_2)dA \tag{5}$$

where A is the area of the PZT patch and h_p is the thickness of the PZT patch. To determine the steady-state power output under harmonic vibration, let the dynamic strain components be harmonic at the same frequency ω for simplicity:

$$S_1 = S_1 e^{j\omega t}, \quad S_2 = S_2 e^{j\omega t} \tag{6}$$

where j is the unit imaginary number, and S_1, S_2

are the strain magnitudes. If the steady-state voltage output is $v(t) = Ve^{j\omega t}$,e quation (5) can be reduced to:

$$V = \frac{j\omega \bar{e}_{31} R_L h_p A(\tilde{S}_1 + \tilde{S}_2)}{j\omega R_L \bar{\varepsilon}_{33}^{s} A + h_p} \tag{7}$$

Therefore, the steady-state power amplitude is as:

$$P = \frac{\omega^2 \bar{e}_{31}^2 R_L h_p^2 A^2 (\tilde{S}_1 + \tilde{S}_2)^2}{\omega^2 R_L^2 (\bar{\varepsilon}_{31}^S)^2 A^2 + h_p^2} \tag{8}$$

The maximum power P_{max} can be obtained at optimal resistance which is obtained from a derivative of the power equation (8) as:

$$\left.\frac{\partial P}{\partial R_L}\right|_{R_L = R_L^{opt}} = 0 \tag{9}$$

then be reduced to:

$$R_L^{opt} = \frac{h_p}{\omega \bar{\varepsilon}_{33}^{s} A} \tag{10}$$

By substituting equation (10) into (8), the maximum power output can be derived as:

$$P_{max} = \frac{\omega \bar{e}_{31}^2 h_p A(\tilde{S}_1 + \tilde{S}_2)^2}{2\bar{\varepsilon}_{33}^S} \tag{11}$$

To achieve the maximum power, the size of the PZT patch can be determined as:

$$A = \frac{h_p}{\omega^{target} \bar{\varepsilon}_{33}^S R_L^{target}} \tag{12}$$

The dielectric permittivity at constant strain and the thickness of the PZT patch are known values. We can also know the external load once the target application is specified. As a result, the optimal size of the PZT patch can be determined.

3. Experimental Validation

Fig. 2 shows the experimental setup. The boundary condition of the PEH skin is fully clamped along the all edges. From the experiment results(Fig. 3), we can find that the output power is maximum at the optimal resistance. These observations are in agreement with the results predicted by analytical analysis.

As shown in Table 1, if we know the resistance and frequency of the target application, the optimal size of the PEH skin can be determined during the design process.

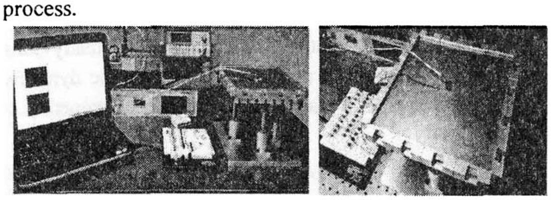

Fig.2 Experimental setup

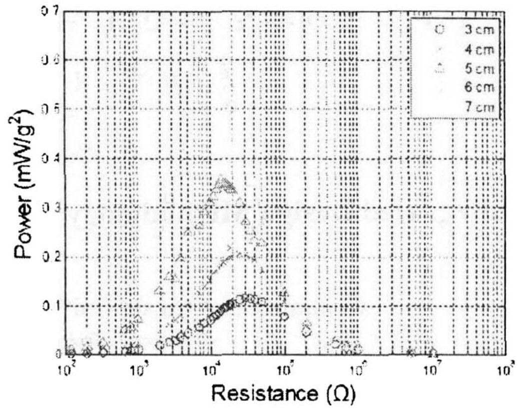

Fig.3 Validation of electric power at optimal resistance

Table 1 Estimation of the PEH skin size

Diameter (cm)	48.65 Hz		69.5 Hz		90.35 Hz	
	Load(Ω)	D.(cm)	Load(Ω)	D.(cm)	Load(Ω)	D.(cm)
3	50.1k	2.95	30.1 k	3.18	25.0k	3.06
4	30.1k	3.80	19.0 k	4.00	14.0k	4.09
5	17.9k	4.93	13.2 k	4.80	10.0 k	4.84
6	12.1k	5.99	10.0 k	5.52	7.0 k	5.78
7	9.0 k6.	95	6.5 k	6.84	5.0 k	6.84

4. Conclusion

The proposed methodology can be used to simultaneously optimize the electrical and mechanical design variables to achieve maximal output power. Because we just consider the resistance in impedance matching, our future work will include the consideration about capacitors and inductors as well as resistance.

Acknowledgements

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References

(1) Heonjun Yoon and Byeng D Youn, 2014, "Stochastic quantification of electric power generated by a piezoelectric energy harvester using a time-frequency analysis under non-stationary random vibrations," *Smart Mater. Struct.* Vol. 23, 045035

(2) Standards Committee of the IEEE Ultrasonics, Ferroelectrics, and Frequency Control Society, 1987, *IEEE Standard on Piezoelectricity*, IEEE, New York.