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Modeling and Comparison of Cantilevered Piezoelectric Energy Harvester with Segmented and Continuous Electrode Configurations

Hongyan WANG^{a,b}, Lihua TANG^c, Xiaobiao SHAN^a, Tao XIE^{*a}, Yaowen YANG^c

^aState Key Laboratory of Robotics and System, Harbin Institute of Technology, Harbin 150001, China; ^bCollege of Computer and Control Engineering, Qiqihar University, Qiqihar 161006, China;

^cSchool of Civil and Environmental Engineering, Nanyang Technological University, 50 Nanyang Avenue, 639798, Singapore

ABSTRACT

Continuous electrode configuration (CEC) has been widely used in piezoelectric energy harvesters (PEHs). A PEH with CEC works around the first resonance efficiently but it suffers from low efficiency due to cancellation effect around higher modes. The use of segmented electrode configuration (SEC) can avoid the cancellation effect around higher modes. To achieve this, the output from each electrode pair on the opposite sides of the strain node needs to be rectified separately. In such a case, the theoretical formulation for power estimation becomes challenging because of some nonlinear electrical components included. In this paper, a method based on combining the equivalent circuit model (ECM) and the circuit simulation is proposed to estimate the power outputs of the cantilevered PEH with the SEC. First, the parameters in the ECM considering multiple modes of the PEH with the SEC are identified from the finite element analysis. The ECM is then established and simulated in the SPICE software. The optimal power outputs from the PEH with the SEC are compared with those from the PEH with the CEC. The results illustrate the advantage of the SEC to enhance the power outputs of a PEH at higher resonance frequencies.

Keywords: Piezoelectric energy harvester, cantilever, electrode configuration, equivalent circuit model

1. INTRODUCTION

Wireless sensor network technology has emerged and provided various applications such as structural health monitoring, environmental monitoring and building automation. However, the batteries used to power these low-power sensing devices carry disadvantages as well, such as large size, limited lifespan and high replacement cost [1]. Vibration energy harvesting provides a promising solution of power supply and has attracted immense research interests owing to its potential to implement low-cost self-powered wireless sensors. The vibration energy in the environment can be converted to useful electricity via piezoelectric [2,3], electromagnetic [4], or electrostatic transductions [5]. Piezoelectric transduction has been widely pursued in small-scale energy harvesting systems [6,7] due to the high power density and ease for application as compared to the other two transductions.

Cantilevered piezoelectric energy harvesters (PEHs) are usually configured with the continuous electrodes along its full length. The energy harvester with the continuous electrode configuration (CEC) is efficient around the first resonance frequency while electrical cancellation will happen around higher resonance frequencies. In some literatures, the segmented electrode configuration (SEC) is proposed to avoid the electrical cancellation [8,9]. However, each electrode pair on the opposite sides of the strain node needs to be rectified separately. Thus, mathematical formulation for power prediction becomes cumbersome as the energy harvesting interface circuit includes nonlinear electrical components.

The equivalent circuit models (ECM) provides another way to study the performance of PEH. The parameters in ECM can be identified using mathematical models or finite element method (FEM) [10-13]. With the established ECM, we can predict the performance of PEH with sophisticated interface circuits such as SSHI [14-18] and SCE [19,20] by using SPICE software. Although ECM of the PEH is available in some literatures, the researches focused on the PEH with CEC, where only single electrical output port provides power to the load.

* xietao@hit.edu.cn; wanghongyan1993@163.com

In this paper, a multi-mode ECM of the cantilevered PEH with SEC is presented, where the PEH has two electrical output ports. The parameters in the ECM are identified from the finite element analysis (FEA). The multi-mode ECM with a standard rectifying interface circuit is simulated in SPICE software. Furthermore, the optimal power outputs of the PEH with SEC around the first two resonance frequencies are predicted. The results are compared with those of the CEC to illustrate the advantage of the SEC to enhance the power output at a higher resonance frequency.

2. EQUIVALENT CIRCUIT MODELING

2.1 Equivalent Circuit Modeling

Figure 1(a) and (b) show the cantilevered PEH with the CEC and SEC, respectively. For the PEH with the bimorph plates, two piezoelectric plates (PZT₁ and PZT₂) are bonded to the top and bottom of the metallic plate, respectively. A proof mass is attached to the free end of the piezoelectric cantilever. The bimorph plates have opposite poling direction and they are connected in series. In Figure 1(a), the surface electrodes of the piezoelectric plates are continuous throughout the full length of the beam. The output terminal is directly connected to a resistor R_L . In Figure 1(b), the electrode pair is discontinuous at the location of the strain node of the second bending mode. The electrode configuration on the left of the strain node is the SEC1 and the other on the right is the SEC2. The two output terminals with SEC1 and SEC2 are connected to the resistors of R_{L1} and R_{L2} , respectively.

Figure 1. Cantilevered PEH with (a) CEC and (b) SEC

The governing equations of the cantilevered PEH with SEC can be written as

$$\begin{cases} \mathbf{P}^T \mathbf{M} \ddot{\mathbf{q}} + \mathbf{P}^T \mathbf{D} \dot{\mathbf{q}} + \mathbf{P}^T \mathbf{K} \mathbf{q} - (\mathbf{P}^T \boldsymbol{\Theta}_1 V_{R1} + \mathbf{P}^T \boldsymbol{\Theta}_2 V_{R2}) = -\mathbf{P}^T \mathbf{B} \ddot{z}_b \\ \boldsymbol{\Theta}_1^T \mathbf{P} \dot{\mathbf{q}} + C_1^S \dot{V}_{R1} + \frac{V_{R1}}{R_{L1}} = 0 \\ \boldsymbol{\Theta}_2^T \mathbf{P} \dot{\mathbf{q}} + C_2^S \dot{V}_{R2} + \frac{V_{R2}}{R_{L2}} = 0 \end{cases} \quad (1)$$

where $\mathbf{M}$, $\mathbf{K}$, and $\mathbf{D}$ are the mass, stiffness, and damping matrices of the piezoelectric energy harvester, respectively; $\mathbf{B}$ is the effective forcing vector; $\ddot{z}_b$ is the excitation acceleration; $\mathbf{P}$ is the eigenvector of the equation $\mathbf{M}\ddot{\mathbf{r}} + \mathbf{K}\mathbf{r} = 0$. $\boldsymbol{\Theta}_1$ and $\boldsymbol{\Theta}_2$ are the electromechanical coupling coefficient of the piezoelectric cantilever with SEC1 and SEC2, respectively; C_1^S and C_2^S are the clamped capacitance of the piezoelectric cantilever for SEC1 and SEC2, respectively; V_{R1} and V_{R2} are the voltage across R_{L1} and R_{L2} , respectively. The modal electromechanical coupling governing equations of the PEH with SEC can be further written as

$$\begin{cases} \ddot{\eta}_i + 2\zeta_i \omega_i \dot{\eta}_i + \omega_i^2 \eta_i - (\chi_{1-i} V_{R1} + \chi_{2-i} V_{R2}) = -b_i \ddot{z}_b \\ \sum_{i=1}^n \chi_{1-i} \dot{\eta}_i + C_1^S \dot{V}_{R1} + \frac{V_{R1}}{R_{L1}} = 0 \\ \sum_{i=1}^n \chi_{2-i} \dot{\eta}_i + C_2^S \dot{V}_{R2} + \frac{V_{R2}}{R_{L2}} = 0 \end{cases} \quad i=1,2 \quad (2)$$

where η_i are the entries in the decoupled displacement vector η ; b_i are the entries in the decoupled modal force coefficient matrix of $\mathbf{P}^T \mathbf{B}$; χ_{1_i} and χ_{2_i} are the entries in the decoupled modal electromechanical coupling matrixes of $\mathbf{\Theta}_1^T \mathbf{P}$ and $\mathbf{\Theta}_2^T \mathbf{P}$, respectively.

Table 1. Analogy between mechanical and electrical domains

Mechanical parameters at i -th mode	Equivalent circuit parameters at i -th mode
Modal coordinate: $\eta_i(t)$	Charge: $q_i(t)$
Modal velocity: $d\eta_i(t)/dt$	Current: $i_i(t)$
1	Inductance: L_i
$2\zeta_i\omega_i$	Resistance: R_i
$1/\omega_i^2$	Capacitance: C_i
Modal force: $-b_i\ddot{z}_b$	Voltage source: $v_i(t)$
Electromechanical coupling: $-\chi_{1_i}, -\chi_{2_i}$	Turn ratio of ideal transformer: N_{1_i}, N_{2_i}

Considering the analogy between the mechanical and electrical domains as listed in Table 1, Equation (2) can be further written as

$$\begin{cases} L_i \ddot{q}_i + R_i \dot{q}_i + \frac{1}{C_i} q_i + (N_{1_i} V_{R1} + N_{2_i} V_{R2}) = v_i \\ -\sum_{i=1}^n N_{1_i} \dot{q}_i + C_1^S \dot{V}_{R1} + I_1 = 0 \\ -\sum_{i=1}^n N_{2_i} \dot{q}_i + C_2^S \dot{V}_{R2} + I_2 = 0 \end{cases} \quad i=1,2 \quad (3)$$

where I_1 and I_2 are the current through the resistors R_{L1} and R_{L2} , respectively.

In Equation (3), setting N_{1_i} and N_{2_i} to N_i and zero, respectively, we can obtain the ECM equations of the cantilevered PEH with CEC as follows:

$$\begin{cases} L_i \ddot{q}_i + R_i \dot{q}_i + \frac{1}{C_i} q_i + N_i V_R = v_i \\ -\sum_{i=1}^n N_i \dot{q}_i + C^S \dot{V}_R + I = 0 \end{cases} \quad i=1,2 \quad (4)$$

where the turn ratio of ideal transformer is $N_i = N_{1_i} + N_{2_i}$; the static clamped capacitance is $C^S = C_1^S + C_2^S$; V_R is the voltage across the resistor R_L ; I is the current through R_L .

For the PEH with SEC, we construct two-branch circuit network accounting for the first two modes, each composed of an inductor, a capacitor, a resistor, an ideal voltage source, and two ideal transformers. Figure 3 shows the multi-mode ECM of the PEH with the SEC1 and SEC2. It should be noted that the parameters identified from FEA such as ideal voltage sources and the transformer ratios may give positive or negative values. However, the circuit simulation software (SPICE) only accepts positive input value. We can handle this challenge through changing the wire connection patterns and the details will be given in the case study.

Figure 2. Multi-mode ECM of cantilevered PEH with SEC1 and SEC2

2.2 ECM Parameters Identified by FEA

Although the parameters in ECM for the cantilevered PEH can be identified from the theoretical analysis, the theoretical derivation is cumbersome. In this section, we use FEM to determine the equivalent circuit parameters of the PEH, which can avoid the tedious calculation from theoretical analysis. The parameters to be identified are L_i , R_i , C_i , N_{1_i} , N_{2_i} and $v_i(t)$. The first five parameters will be identified from the admittance and the impedance of the PEH, and the last parameter $v_i(t)$ will be defined from the short-circuit charge response with base excitation.

ECM of PEH in Actuator Mode

To identify the equivalent circuit parameters using FEM, we need establish the ECM the PEH without the ideal transformers. Setting N_{2_i} to zero in Figure 2, i.e., SEC2 is short-circuited. The parameters v_i , L_i , R_i , C_i can be converted from the left side of the transformer (N_{1_i}) to the right side, as shown in Figure 3(a). The voltage source (v_{1_i}), the motional inductance (L_{1_i}), the motional resistance (R_{1_i}) and the motional capacitance (C_{1_i}) of SEC1 are determined as:

$$v_{1_i} = v_i / N_{1_i}, L_{1_i} = L_i / N_{1_i}^2, R_{1_i} = R_i / N_{1_i}^2, C_{1_i} = C_i N_{1_i}^2 \quad (5)$$

As the PEH works in actuator mode, $v_{1_i} = 0$. The equivalent circuit can be further simplified as shown in Figure 3(b). It can be seen from Figure 3(b) that the equivalent circuit is actually an RLC circuit network. Each RLC branch represents one vibration mode of the PEH.

Figure 3. The ECM of PEH without ideal transformer (a) in transducer mode (b) in actuator mode. Given short circuit condition for SEC2

Similarly, setting N_{1_i} to zero in Figure 2, i.e., SEC1 is short-circuited. We can obtain another RLC circuit network. The electrical parameters of SEC2 can be determined as:

$$v_{2_i} = v_i / N_{2_i}, L_{2_i} = L_i / N_{2_i}^2, R_{2_i} = R_i / N_{2_i}^2, C_{2_i} = C_i N_{2_i}^2 \quad (6)$$

where $v_{2_i}(t)$, L_{2_i} , R_{2_i} and C_{2_i} are the voltage source, the motional inductance, the motional resistance and the motional capacitance of SEC2, respectively.

Finite element model of PEH with SEC

Figure 4 shows the finite element model of the PEH with SEC using ANSYS software. SOLID5 element is applied for the piezoelectric layers and SOLID45 element is applied for the substrate layer and proof mass. The piezoelectric layers are made from polarized PZT-5H, and the substrate layer and proof mass is made from brass. The signs of the piezoelectric constants for the top and bottom piezoelectric plates in defined material property are different to obtain the opposite polar direction to ensure the symmetric bimorph in series. The voltage DOFs on each electrode surface of piezoelectric layers are coupled to ensure a uniform electrical potential. Table 2 lists the material and geometric properties of the PEH with SEC for case study, where the location of the strain node ($x=L_1$) for the second bending mode is calculated according to the literature [8]. The 3-D properties of PZT-5H parameters for FE model are available in the literature [21].

Figure 4. Finite element model of PEH with SEC

Table 2. Properties of cantilevered PEH with SEC

Item	Value
Density of piezoelectric layer (kg/m ³)	7500
Density of substrate layer (kg/m ³)	8920
Stiffness of substrate layer (GPa)	113
Rayleigh damping constant α	21.2018
Rayleigh damping constant β	1.6697e-5
Length of total beam, $L+L_t$ (mm)	60
Length of active beam, L (mm)	50
Length of proof mass, L_t (mm)	10
Length of SEC1, L_1 (mm)	15
Length of SEC2, $L+L_t-L_2$ (mm)	44.5
Width of beam and proof mass, b (mm)	20
Thickness of piezoelectric layer, h_p (mm)	0.2
Thickness of substrate layer, h_s (mm)	0.3
Thickness of proof mass, h_t (mm)	5

Identification of C_i , L_i , R_i , N_{1_i} and N_{2_i}

As a unit harmonic voltage $V(t)=e^{j\omega t}$ is applied to SEC1, where SEC2 is short-circuited, there is a complex charges $\bar{Q}_1$ generated in the electrode surface of SEC1. We can obtain the admittance Y_1 and impedance Z_1 of SEC1 as

$$Y_1 = \frac{i(t)}{V(t)} = \frac{j2\pi f \bar{Q}_1 e^{j\omega t}}{e^{j\omega t}} = j2\pi f \bar{Q}_1 \quad (7)$$

$$Z_1 = \frac{1}{Y_1} = \frac{1}{j2\pi f \bar{Q}_1} \quad (8)$$

where j is the imaginary unit; f is the excitation frequency and $\omega=2\pi f$. The admittance and impedance curves of the PEH as the function of the excitation frequency around the first two vibration modes are plotted in Figure 5(a) and 5(b), separately. In Figure 5(a) and 5(b), the admittance Y_1 and the impedance Z_1 can be expressed as

$$\begin{cases} Y_1 = G_1 + jB_1 \\ Z_1 = R_1 + jX_1 \end{cases} \quad (9)$$

where G_1 and B_1 are the conductance and the susceptance, respectively. R_1 and X_1 are the resistance and the reactance, respectively.

Figure 5. Admittance and impedance of SEC1 around the first two vibration modes: (a) admittance (b) impedance

The parameters C_{1_i} , L_{1_i} and R_{1_i} of SEC1 around the i -th vibration mode can be identified as

$$\begin{cases} C_{1_i}^d = B_{1_i} / (2\pi f_{sc_i}) \\ C_{1_i} = C_{1_i}^d \left[(f_{oc_i} / f_{sc_i})^2 - 1 \right] \\ L_{1_i} = 1 / \left[(2\pi f_{sc_i})^2 C_{1_i} \right] \\ R_{1_i} = 1 / (G_{1_i})_{\max} \end{cases} \quad i=1,2 \quad (10)$$

where $C_{1_i}^d$ is the termed damped capacitance; f_{sc_i} and B_{1_i} are the short circuit resonance frequency and the susceptance, respectively, where the conductance G_{1_i} is the maximum; f_{oc_i} is the open circuit resonance frequency, where the resistance R_{1_i} is the maximum. Furthermore, the transformer ratio N_{1_i} can be identified as

$$N_{1_i} = 1 / \sqrt{L_{1_i}} \quad (11)$$

According to Equations (5) and (11), we can determine the other three parameters L_i , R_i and C_i . Similar procedure can be applied for SEC2, where SEC1 is short-circuited. According to the admittance and impedance curve of SEC2, we can determine the damped capacitance $C_{2_i}^d$ and the ideal transformer ratio N_{2_i} of SEC2.

Identification of Ideal Voltage Source $v_i(t)$

To determine the ideal voltage source $v_i(t)$, both SEC1 and SEC2 are defined as short-circuit condition and a harmonic base acceleration is applied to the energy harvester. We can obtain the charge response q_{1_i} and q_{2_i} from SEC1 and SEC2 at the short circuit resonance frequency f_{sc_i} , respectively. With the parameters obtained from SEC1 or SEC2, we can define v_i as

$$v_i = j2\pi f_{sc_i} R_{1_i} N_{1_i} q_{1_i} = j2\pi f_{sc_i} R_{2_i} N_{2_i} q_{2_i} \quad (12)$$

In Equation (12), it can be seen that when the signs of q_{1_i} and q_{2_i} obtained from FEA are different, we can change the sign of the ideal transformer ratios N_{1_i} or N_{2_i} to keep the same sign of v_i . The ECM parameters of the PEH with SEC determined from FEA are listed in Table 3.

Table 3. Parameters of ECM of PEH with SEC determined from FEA

i -th mode	L_i	R_i	C_i	N_{1_i}	N_{2_i}	v_i	$C_{1_i}^d$	$C_{2_i}^d$
1	1	20.7	1.58E-5	0.0113	0.0098	-1.0789	1.69E-8	5.26E-8
2	1	138.23	1.38E-7	0.0787	-0.1819	-0.3855	1.60E-8	4.77E-8

3. POWER EVALUATION OF PEH WITH SEC

Figure 6 and 7 show the multi-mode ECM for the proposed PEH with SEC and CEC with the practical DC interface circuits, respectively. In Figure 6, two electrical ports are connected to two separate rectifiers to avoid the electrical cancellation, and then provide power to a common load. In Figure 7, a single electrical port is connected to the rectifier, and then provides power to the load. Note that, as the SPICE software only accepts positive input values, we can avoid the sign problem by changing the wire connection pattern. For example, at the first mode, the ideal voltage source v_1 is negative. Thus, the terminals of v_1 are swapped, as shown in Figure 6. At the second mode, the ideal transformer ratios N_{2_2} and the ideal voltage source v_2 are negative. Thus, the terminals of both N_{2_2} and v_2 are swapped. In addition, since two ideal transformers (N_{1_1} and N_{1_2}) represent the coupling of SEC1 at two modes, their output terminals should be connected to the clamped capacitance C_1^S from SEC1. Similarly, the output terminals of N_{2_1} and N_{2_2} should be connected to the clamped capacitance C_2^S from SEC2. Here, to achieve a more accurate approximation, we use the damped capacitances $C_{1_2}^d$ and $C_{2_2}^d$ at the second mode to replace the clamped capacitance C_1^S and C_2^S , respectively.

Figure 6. System diagram of cantilevered PEH with SEC

Figure 7. System diagram of cantilevered PEH with CEC

Figure 8 compares the optimal power outputs from the PEH with SEC and CEC near the first two vibration modes. It can be seen from Figure 8(a) that the optimal power output of the SEC are almost the same with that of the CEC at the first resonance. However, at the second resonance, the optimal power output of the SEC is two times that of the CEC, as shown in Figure 8(b).

Figure 8. Comparison of optimal power outputs with SEC and CEC at (a) 1st mode and (b) 2nd mode under excitation of 9.8m/s^2

4. CONCLUSIONS

In this paper, a method based on equivalent circuit modeling and circuit simulation is proposed to estimate the power outputs of the cantilevered PEH with the SEC. The parameters in the ECM considering multiple modes are identified by FEA. The multi-mode ECM of the PEH connected with multiple rectifying interface circuit is then established and simulated in the SPICE software. With the proposed ECM-based modeling method, we can predict the power outputs of the PEH with SEC around multiple resonance frequencies. The optimal power outputs of the SEC are compared with those of the CEC. The results show the SEC can improve power magnitude by two times as compared with the CEC at the second resonance frequency. Hence, using SEC is an effective means for PEH to enhance power output at a higher resonance frequency.

5. ACKNOWLEDGMENTS

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