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Electric Power Output Maximization for Piezoelectric Energy Harvester by Optimizing Resistive Load

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1. Introduction

Vibration energy harvesting can be utilized via several different transduction mechanisms the most common and effective are transducers utilizing triboelectric effect [1], electrostatic, electromagnetic and piezoelectric transduction mechanisms. These have been widely compared and discussed in [2- 4] except the triboelectric transduction mechanism which is quite new in comparison with the latter. In this paper the piezoelectric transduction mechanism will be discussed and investigated more widely. Direct piezoelectric effect is utilized here, converting the ambient vibrations to mechanical strain in the substrate layer and to electric charge in the piezoelectric material layer via electromechanical coupling as described in [5]. It is usually desired for the harvester to be subjected to ambient harmonic vibrations of frequency matching transducers resonant frequency for maximization of harvester vibration amplitude and strain and thus voltage/power output. This type of harvester is usually a cantilevered transducer with one or several piezoelectric material layers attached to its surface [6]. Transducers operating in first natural mode usually have one (unimorph) or two piezoelectric material layers (bimorph) covering both surfaces of the cantilever. Transducers operating in higher vibration modes are forced to have multiple pairs or piezoelectric layers due to strain nodes as explained by [7-8]. Segmentation of piezoelectric layers is necessary to avoid charge cancelation. Piezoelectric layers can be connected in series for output voltage maximization or in parallel for current maximization [9-10]. Power maximization from such devices can be achieved by optimizing the mechanical domain parameters or electrical domain parameters. In this paper an investigation of AC electrical power output maximization by optimal resistive load for transducers operating in higher vibration modes is presented.

2. Theoretical background and FEM Modelling of PVEH with optimal resistive load

In this paper AC power output of a PVEH operating in second resonant mode is investigated. Effect of varying resistive load on power output of PVEH is investigated as well as AC power output characteristics of layers connected in parallel (Figure 2a) or series (Figure 2b) connection. The load bearing layer is made of aluminium and PVDF (polyvinylidene fluoride) is chosen as piezoelectric material due to its flexibility and lightness. Havier and harder piezo-ceramics was not chosen because of its significant contribution to the overall dynamics of the PVEH, due to its relatively high mass and hardness while the effect of PVDF can be neglected. Consecutive equations of the load bearing and piezoelectric materials are more deeply explained by [12]. The first PVDF layer is mounted from the fixed end to the strain node [11], the second from the strain node up to the cantilever end on the opposite face of the cantilever. The PVDF layers attached are of same polarization thus the charge produced is of same sign and can be harvested with a relatively simple circuit. Cantilever displacement in y direction in second natural mode of PVEH and electric potentials of PVDF layers are shown in Figure 1.

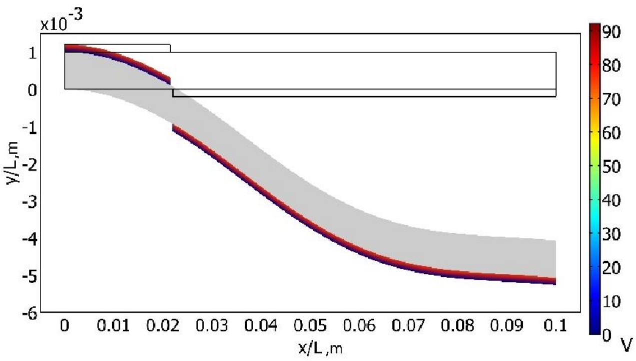

Fig. 1. Second natural mode of PVEH and electric potentials of piezoelectric layers.

The load resistance R_l is connected in series with the piezoelectric elements in the first case and in parallel in second case and produce AC current. A second resistive load could also be introduced to represent the voltage leakage and losses due to wires but in this case it was neglected. Geometric parameters as well as other mechanical characteristics of PVEH can be found in Table 1. The modal analysis of the system was done to obtain the resonant frequency. Harmonic analysis was performed to obtain the electric power output of PVEH versus load R_l.

FE mesh with 700 elements per length of the cantilever was implemented. A coupled piezoelectric-circuit finite element model (CPC-FEM) was used for solving this problem. System was modeled using COMSOL multi-physics with SPICE piezoelectric circuit attached. Harmonic base excitation of frequency matching transducers second resonant frequency was used with an acceleration of 1.3g. Excitation parameters are varied by the frequency ω_n of the time-dependent force *f(t)*. Quadratic Lagrange element type with second-order polynomial approximation was used.

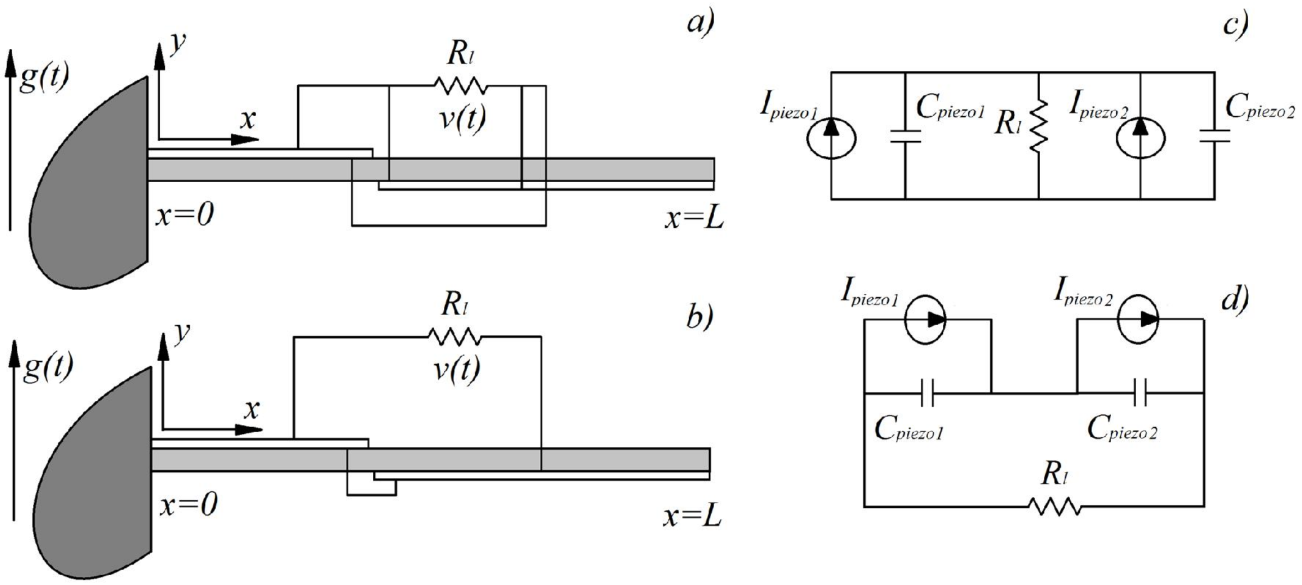

Fig. 2. Piezoelectric cantilever under translational base excitation with PVDF segments connected a) in parallel, b) in series. Electrical circuit of PVEH with piezoelectric outputs connected in c) parallel and d) series connection.

Table 1.
Mechanical and geometrical properties of substrate layer and PVDF properties.

Parameter	Substrate layer	Parameter	PVDF
Density, kg/m^3	2700	Piezoelectric strain constant, d_{31}, (pC/N)	23
Elastic modulus, N/m^2	$0{,}69 \times 10^{11}$	Piezoelectric stress constant, d_{31}, (Vm/N)	216×10^{-3}
Poisson's ratio	0,33	Electromechanical coupling factor, k_t,	12%
Length, L, m	0,1	Capacitance, C, nF	1,4-2,8
Width a, m	0,01	Young's modulus, Y, N/m^2	4×10^9
Thickness b, m	0,001	Permittivity, ε, F/m	110×10^{-12}
PVDF Segmentation line, m	0,0238	Mass Density, ρ, kg/m3	1780
		Thickness, t, μm	45

The piezoelectric element can be modelled as equivalent circuit of a current source I_{piezo} in parallel with a capacitor C_i as shown in Figure 1c) and Figure 1d). Piezoelectric PVEH has high impedance in order of MΩ thus it may be considered as purely capacitive element with capacitance of pF order. The capacitance of the piezoelectric element C_p can be found from Equation (1), the impedance of piezoelectric element Z_p can be found as shown in Equation (2).

$$C_p = \frac{K\varepsilon_0 A}{t} \quad (1)$$

$$Z_p = \frac{1}{2\pi f C_p} \quad (2)$$

Here, A is the surface area of the piezoelectric layer and t is thickness. K is dielectric constant, which is ratio between permittivity of piezoelectric material ε and permittivity of free space ε_0. In Equation (2) f is excitation frequency. For maximization of power transfer the load resistance has to be matched with internal impedance of piezoelectric elements of the transducer which will be different for series and parallel connections of piezoelectric elements. The optimal load resistance is equal to equivalent impedance of combined internal impedances of PVDF layers. The calculated combined impedance of both PVDF

layers for series connection is $Z_{pS} = 127168\ \Omega$ and parallel connection - $Z_{pP} = 29355\ \Omega$. For series connection the combined impedance is simply a sum of impedances of both piezoelectric layers $Z_{pS} = Z_{p1} + Z_{p2}$ and $\frac{1}{Z_{pP}} = \frac{1}{Z_{p1}} + \frac{1}{Z_{p2}}$ for parallel connection.

2. Simulation Results

The second resonant frequency found from modal analysis was 644 Hz. The frequency-amplitude response obtained from harmonic analysis is shown in Figure 3 and confirms the modal analysis results. The obtained eigen-frequency was then inserted into the harmonic analysis models to obtain the voltage and current outputs with varying load resistances for series and parallel connections. The obtained characteristics are shown in Figures 4-6 - Voltage output, current output and PVEH electric power output respectively. From Figure 4 it can be seen that the voltage output of series connection is nearly double of that obtained from parallel connection and as voltage output increases with increasing load resistance, drop in output current can be observed in Figure 5. Figure 6 show that similar power output (8% difference) is obtained from both series and parallel connections.

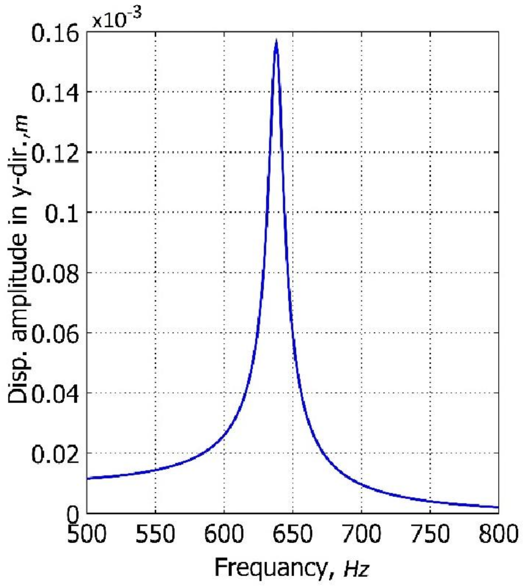

Fig. 3. Amplitude-Frequency response characteristics of the tip of the cantilever

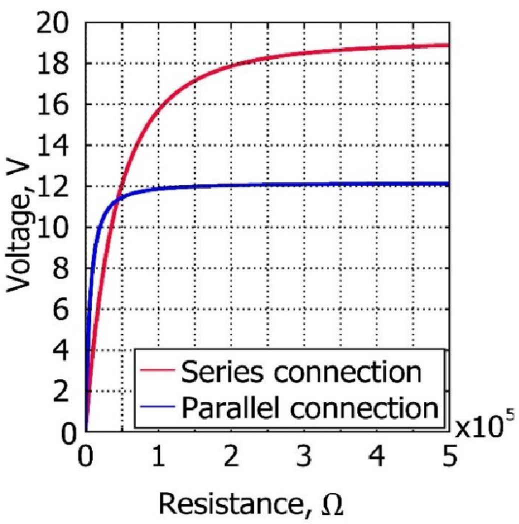

Fig. 4. Voltage output of parallel and series connection

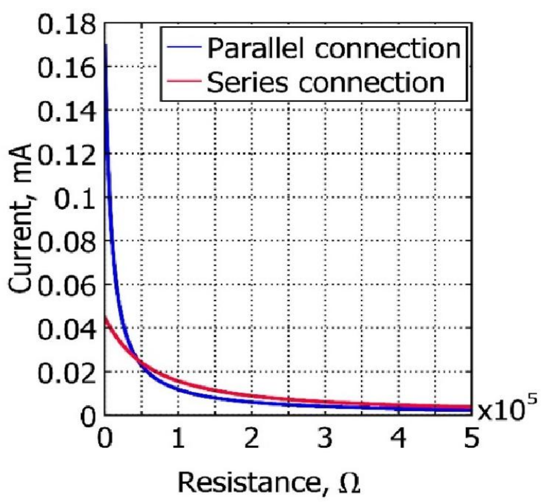

Fig. 5. Current output of parallel and series connection

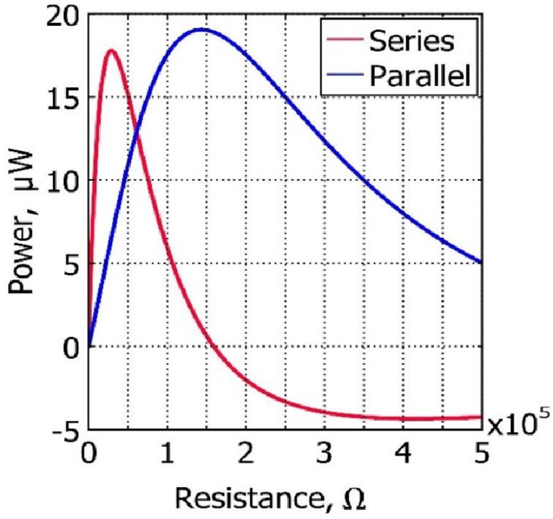

Fig. 6. Power output of parallel and series connection

Peak power output values are reached at optimal resistances and it can be seen that the optimal resistances for both setups is different. Optimal resistance for parallel connection is found to be at 127 kΩ and 29 kΩ for series connection. The results comply well with calculated values of the impedance of piezoelectric element Z_{pP} and Z_{pS} .

3. Conclusions

1. The simulation results comply well with theoretical calculations of optimal resistive load and it is obvious that resistive load vary significantly for parallel (127 kΩ) and series (29 kΩ) connected piezoelectric material layers.
2. Appropriate connection can be chosen if larger output voltage or current is desired.
3. The difference between output power of PVEH connected in series (17.5 μW) and in parallel (19.2 μW) connections is small (8%) but the outputs were expected to be equal with same initial conditions. For this the impact of varying resistive load on dynamics of PVEH is suspected.
4. Significantly larger power outputs are expected from PVEH using piezo-ceramics instead of PVDF due to larger piezoelectric constant but the effect on dynamics of the cantilever has still to be investigated.

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ELECTRIC POWER OUTPUT MAXIMIZATION FOR PIEZOELECTRIC ENERGY HARVESTER BY OPTIMIZING RESISITIVE LOAD

S u m m a r y

In this paper electric power output maximization of piezoelectric energy harvester excited in second natural frequency is presented. Optimal resistive load was found using frequency response analysis. FE model of the harvester system and energy harvesting circuit attached is presented. Effect of varying resistive load on dynamics of the harvester is shown and explained.

Keywords: Piezoelectricity, energy harvesting, power output, higher modes.