Improving the Power out of a Piezoelectric Energy Harvester Using Segmented Electrodes

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ABSTRACT

Vibration-based EH (Energy Harvesting) using piezoelectric materials have been investigated by several research groups with the aim of harvesting maximum energy and providing power to low-powered wireless electronic systems for their entire operational life. The main areas of research includes improvements in mathematical modelling, optimization of harvester geometry, developments in electrical circuitry, advancements in charge storage devices and investigating various piezoelectric materials to achieve maximum power output. This paper investigates and compares the electrical power output with whole length electrodes and with segmentation of electrodes for the same harvester length. It is found that the voltage generated by one electrode of length *l/2* of the direction-fixed tip system is significantly greater than that produced by one electrode of length *l* of the free tip system. This paper also verifies the fact that segmentation of electrodes reduces the effect of strain nodes and charge cancellation particularly at higher mode frequencies. The paper presents the simulation results using DSM (Dynamic Stiffness Matrix) which is a compact method of modelling piezoelectric beams.

Key Words: **Vibration, Energy Harvesting, Segmented Electrodes, Piezoelectric, Circuity, Mechanical Energy, Ambient Vibration.**

1. INTRODUCTION

The concept of extracting energy from ambient sources and accumulating or storing it for a useful purpose is called EH. The concept of harvesting energy from ambient sources is not new and its history dates back to the windmill and the waterwheel [1]. For many decades, researchers have been developing techniques to harvest energy from heat and other ambient sources. However, owing to the low energy conversion efficiency and a higher power requirement by many applications, the field of EH did not attract enough attention in the past [1].

With recent advances in low-powered wireless electronic devices and a global ambition of harvesting "green energy" from ambient sources, the area of EH has garnered greater interest over the past few years [1]. The drastic reduction in size and power consumption of modern electronic devices has encouraged researchers and industry to explore schemes to implant an endless power supply mechanism within these systems, which can harvest energy from their surroundings for their whole life span [1].

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PVEH (Piezoelectric Vibration Energy Harvesting) has been the subject of recent rigorous research with the ultimate ambition of developing self-sufficient autonomous wireless electronic systems. Such systems could harvest energy from ambient vibrations for their entire service life, eliminating the need for traditional electrochemical batteries. This paper concerns the modelling results of PVEH beams using segmented electrodes in order to investigate the augmentation in electrical output for a given mechanical vibration input than the electrical output obtained with a similar length beam but with whole electrodes.

Typically, a piezoelectric energy harvester is a cantilevered beam with one or more piezoelectric layers, bonded to a non-piezo material that is referred to as a “shim”. The harvester is attached to a vibrating host structure (Fig. 1), and the dynamic strain induced in the piezoelectric layers generates an alternating voltage output across the electrodes covering the piezoelectric layers [1]. In return, the generated voltage modifies the dynamic properties of the harvester (i.e. damping, stiffness and resonance frequency). In order to understand the idea of PVEH, Fig. 1 presents the block diagram of PVEH mechanism.

The main advantages of using piezoelectric materials in vibration EH are their higher power densities and ease of implementation [2]. Moreover, owing to the well-established thin-film and thick-film fabrication techniques, piezoelectric energy harvesters can be fabricated both in macro-scale and micro-scale easily [3]. It is also important to note that the lifetime of a piezoelectric harvester can almost be unlimited if the applied force and working temperature are kept within the operational range of the material [1]. Furthermore, piezoelectric technology is sufficiently mature and a broad range of piezoelectric materials are readily available to use in HV (Energy Harveser). It is also important to note that, over the past few years, there have been several research papers presenting mathematical modelling aspects [4-7] of the energy harvester and also presenting the experimental validations [2, 7-10] to verify the mathematical models.

In PVEH, the amount of electric charge collected by the electrodes is the integral of the normal component of electric displacement over the electrode area and the electric displacement field induced in the PZT during the vibratory motion is a function of the strain distribution over its length [11]. In the piezoelectric beams, at higher mechanical modes, if the strain distribution and the respective electric displacement component changes sign under a continuous full electrode pair, the cancellations occur and the electric charge collected by the electrodes diminishes dramatically [11]. Therefore, in order to avoid

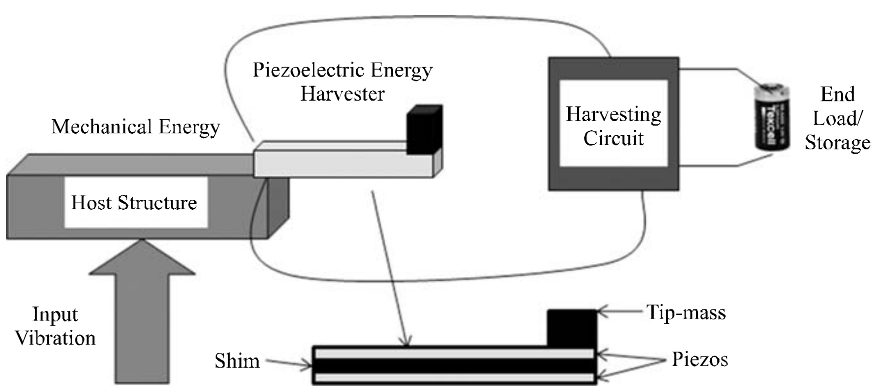


FIG. 1. BLOCK DIAGRAM OF A TYPICAL PVEH MECHANISM [1]

these charge cancellations and to reduce the amount of charge losses, the use of continuous electrodes is not a suitable choice and, hence, the idea of using segmented electrodes emerged. The electrodes are segmented in such a way to cover the strain node effects of higher vibration modes.

In the following sections, an analytical study of using segmented electrodes to enhance the net power out of a PVEH system is presented. It is shown in this paper that almost double power output can be achieved if the electrodes of the piezoelectric energy harvester can be segmented as compared to the whole length electrode of the same harvester beam.

2. METHODOLOGY

The electrical EH potential of two different types of PVEH beams, segmented and whole length electrodes, is presented in this section. The parameters of the PVEH bimorphs used for this study are presented in **Table 1** which are the same as were used in [5]. Unless otherwise stated, the results refer to a series-connected bimorph as shown in Figs. 2-3. A moderately-sized tip mass M_T=0.5m_b is included to incorporate all features of the modelling procedure. The damping ratios for the first two modes are taken as ζ_1=0.0166, ζ_2=0.0107, unless otherwise stated. The DSM mathematical model [5] is used for simulations and analysis as it is compact and obviates the need for modal summations.

Fig. 2 shows a direction fixed piezoelectric cantilever beam having whole length *'l'* electrode. The system is connected to an impedance load of 'Z' as shown in Fig. 2.

Whereas, in Fig. 3, the PVEH beam is modified by fixing the direction of its right end, segmenting its electrodes into two halves of lengths *'l/2'* and connecting equal external impedances *Z* to each segment. The tip constraint would create a point of greatest slope at the midpoint P which increases the generated voltage.

TABLE 1. PARAMETERS OF THE BIMORPH BEAM USED IN ANALYSIS

Thickness of Piezos h_p(mm)	0.267	Length of Beam l (mm)	60
Thickness of Metal Layer h_{sh}(mm)	0.300	density of piezo (Kg/m^3)	7800
Young's Modulus of Piezo (GPa)	62	density of shim (Kg/m^3)	2700
Young's Modulus of Metal Shim (GPa)	72	piezoelectric strain coefficient d_{31} (m/V)	-320x10^{-12}
Width of beam *b* (mm)	25	permittivity at constant stress T_{33} (F/m)	3.3646x10^{-8}

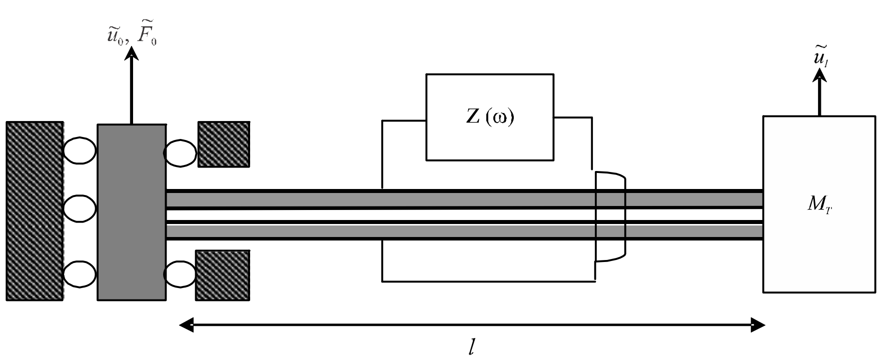


FIG. 2. DIRECTION-FIXED BASE/TIP FREE CANTILEVER BEAM WITH END MASS

Alternatively, the arrangement in Fig. 3 can also be developed in practice through a symmetric setup comprising a beam of length 2*l* direction-fixed at both ends with a central mass of $2\hat{M}_T$, electrodes segmented into four equal parts, and an external impedance of *Z* connected to each segment [5]. For the Fig. 3, the 6x6 global dynamic stiffness matrix $\mathbf{D_g}$ is assembled as presented in the work of reference [5]. By inverting this matrix equation and setting $\widetilde{F}_1$, $\widetilde{\Gamma}_1$, $\widetilde{F}_2$, $\widetilde{\theta}_0$ and $\widetilde{\theta}_2$ to zero, $\widetilde{F}_0$, $\widetilde{\Gamma}_0$ and $\widetilde{\Gamma}_2$ can be expressed in terms of $\widetilde{u}_0$.

Where $\widetilde{F}_1$, $\widetilde{\Gamma}_1$, $\widetilde{F}_2$, $\widetilde{\theta}_0$ and $\widetilde{\theta}_2$ are force and displacement components of DSM. The maximum slope $\widetilde{\theta}_1$ can then be expressed in terms of $\widetilde{u}_0$, enabling the calculation of the voltage FRF as presented in [5].

3. RESULTS AND DISCUSSIONS

The performance of this direction-fixed tip system of Fig. 3 was compared with that of the previous free-tip system, illustrated in Fig. 2, for the same bimorph parameters shown in Table 1 and a series piezo connection for each electrode segment. In this work, the structural and ambient damping parameters were the same for both systems of Figs. 2-3. In order to tune the both systems at the same resonance frequency, the tip mass of the direction-fixed tip system was raised to $2.578m_b$ (from $0.5m_b$), under short circuit conditions [5]. Fig. 4(a) shows the variation in voltage FRF (per electrode segment) at the first resonance and the corresponding specific mean power, for different resistive loads. It is clear that the voltage generated by one segmented electrode of length *l/2* of the direction-fixed tip system is significantly greater than that produced by one electrode of length *l* of the free tip system. Consequently, the mean power per unit piezo volume is much greater if the electrodes of the energy harvester are segmented. Furthermore, it is important to note in Fig. 4(c) that the tuned frequency range of the direction-fixed tip system is marginally greater than that of the free-tip system, thereby increasing the effective bandwidth of the energy harvester.

A piezoelectric beam element can be incorporated as a member of a two/three dimensional assembly using the methodology presented in [5] to include longitudinal vibration. Since the format of the elemental dynamic stiffness matrix is similar to an FE (Finite Element) matrix, it can be incorporated into the FE model of a complex structure and used in frequency domain analysis. It is noted that the above described matrix assembly procedure assumes that the individual piezoelectric segments are electrically not connected to each other. The above described assembly process would need to be modified to accommodate electrically interconnected segments.

This is illustrated in Fig. 4 that the vibration modes of a cantilevered beam other than the first fundamental mode have certain strain nodes where the dynamic strain

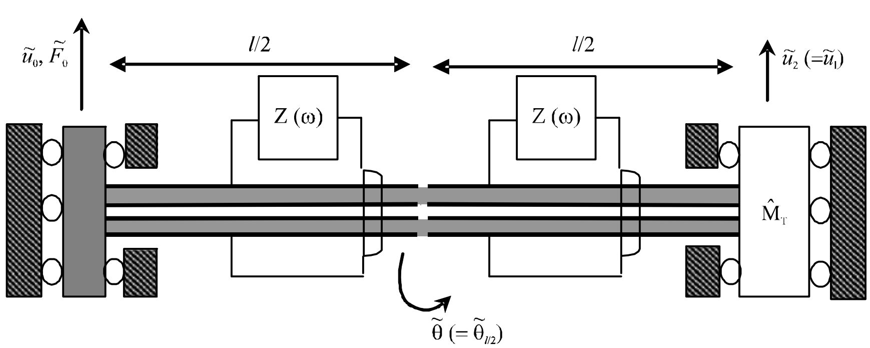
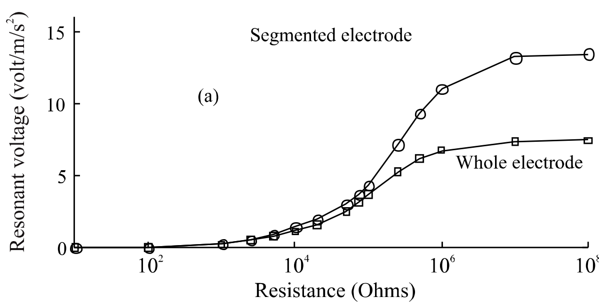
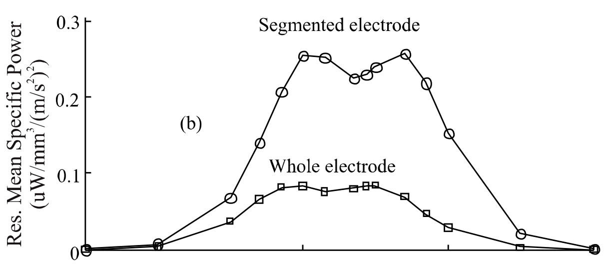


FIG. 3. DIRECTION-FIXED BASE/DIRECTION-FIXED TIP HARVESTER WITH SEGMENTED ELECTRODES

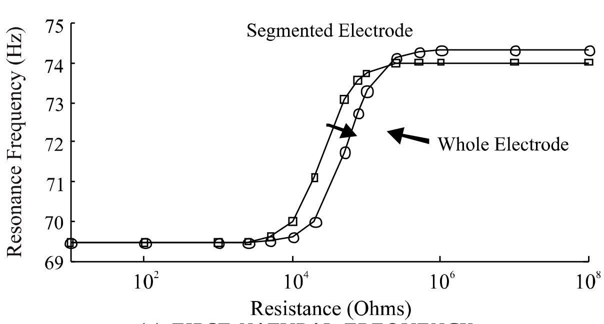
distribution at the thickness level changes sign along the direction of the length of the beam. In this work, it is demonstrated that covering the strain nodes of vibration modes with continuous electrodes results in cancellation of the electrical outputs, positive charge cancelled out with negative charge and vice versa, and, hence, the net electrical voltage and specific power is reduced substantially as can be seen in Fig. 4(a-b). However, making the continuous electrodes in segments at the strain node points, results almost double the electrical energy as can be harvested from single continuous electrode.



(a) GENERATED VOLTAGE AT FIRST RESONANCE



(b) MEAN SPECIFIC POWER AT FIRST RESONANCE



(c) FIRST NATURAL FREQUENCY

FIG. 4. COMPARISON OF SYSTEMS IN FIGS. 2-3 OVER A RANGE OF RESISTIVE LOADS (Z)

Furthermore, it is noted that the FRFs (Frequency Response Functions) derived from DSM, or any other method, can be used in problems where the base-excitation u_0 is non-harmonic [5]. In such cases the FRFs define the ratio of Fourier transforms of the respective output to input (for deterministic excitation) or the ratio of the cross/auto power spectra (for random excitation) [5]. Hence, the solution is achievable by appropriate transformation between the time and frequency domains. It is noted by Adhikari, et. al. [12] that in many applications the ambient vibration is random and broadband. The accurate solution provided by DSM over a wide frequency range makes it more useful in such applications than single-degree of freedom or single-mode approximations.

4. CONCLUSION

This paper presents the effects of segmentation of electrodes of piezo beam on its energy harvesting capabilities. It is found that the voltage and the specific power of the segmented electrode energy harvester increased significantly, around its first mode for a range of resistor loads. The findings revealed the importance of the segmentation of electrodes and the application of a tip rotational restraint as it can enhance the net output to almost double than the traditionally employed cantilever energy harvesting system. Furthermore, it was also found that the effective tuned frequency range of the direction-fixed tip (segmented electrodes) system is marginally increased than that of the free-tip system, thereby increasing the effective operating bandwidth of the energy harvester. This increased effective bandwidth enables PVEH system to harvest more energy.

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