Sensors & Transducers, Vol. 22, Special Issue, June 2013, pp. 133-138

Sensors & Transducers

Modeling and Simulation of Piezoelectric Vibration Generator for Powering Wireless Sensor Networks

[1] HE Qing, [1, 2] LAN Lan, [3] YAN Zhen, [4] ZHAO Xiaotong, [1] DU Dongmei
[1] Key Laboratory of Condition Monitoring and Control for Power Plant Equipment,
Ministry of Education, School of Energy Power and Mechanical Engineering,
North China Electric Power University, Beijing 102206, China
[2] Sinohydro Renewable Energy Co., LTD, Beijing 100048, China
[3] School of Mechanical and Electric Engineering, Agricultural University of Hebei,
Baoding 071001, China
[4] Division of Electric Power System, China Electric Power Research Institute, Beijing 100192, China
Tel.: +86-10-61772270, +86-10-61772803
E-mail: hqng@163.com

Received: 15 April 2013 /Accepted: 20 June 2013 /Published: 28 June 2013

Abstract: Micro piezoelectric vibration generator with high energy density may provide infinite and continuous energy for wireless sensor network. In order to improve generating capacity under given dimension, aiming at external force and displacement incentive environment, mathematics model of piezoelectric cantilever generator generating capacity are established, and influence law of unimorph and bimorph piezoelectric generator structural parameter on output voltage are analyzed by finite element simulation. The results show that on external force incentive environment, the output voltage increase linearly while length increase and decrease inverse proportion while width increase; on displacement incentive environment, the output voltage decrease while length increase and don't change while width vary; meanwhile, relation between thickness ratio and output voltage isn't affected by incentive environment, and bimorph piezoelectric generator with low thickness ratio should be selected at first for obtaining higher output voltage. *Copyright © 2013 IFSA.*

Keywords: Wireless sensor network, Vibration energy harvesting, Piezoelectric vibration generator, Microcantilever.

1. Introduction

Currently, wireless sensor network (WSN) technology which detect and monitor structure of architecture, road and bridge etc have rapid development. The demands of volume, life and energy density of power supply is more and more strict because of high density and micro dimension of net nodes, and traditional supply mode of chemical battery have not meet demand of WSN power supply. So, new power supply mode has become the urgent problem, which solves the development bottleneck of WSN.

If solar, heat and vibration energy which are ubiquitous green energy in nature can be converted to electric energy, WSN would be provided infinite and continuous energy and thus attract particular attention recently [1-6].

Vibration generator adopting electromagnetic, static or piezoelectric principle [7-13] not only can conquer the flaw of solar battery needing light environment, but also can conquer the flaw of heat generator needing temperature grads environment, in which piezoelectric generating with the simple structure, small size, pollution-free, low cost and large energy density has become research hot of power supply of WSN [14-15]. However, output power of piezoelectric generating is still limited now, so it cannot be more abroad applied. How to enhance efficiently the generating capacity of piezoelectric generating equipment is a key question to solve today [16].

In recent years, many studies have shown that piezoelectric generating capacity depends mainly on the material properties, structural parameters, frequency and incentive method etc of piezoelectric vibrator. L. F. Lou et al [17] analyze the influence of thickness ratio, length and width etc structural parameter on output voltage by establishing simulation model of bimorph microcantilever generator (BMG), however accuracy of simulation results need further verification because mathematical theory models and experiment system aren't established. J. W. Kan et al [18] analyze the influence of material properties and thickness ratio etc structure and scale parameter on generating capacity by mathematics and simulation model of unimorph microcantilever generator (UMG) and BMG. J. B. Yuan et al [19] design generating testing system of UMG, and verify finite element simulation results of influence law of thickness ratio on generating capacity by experiment.

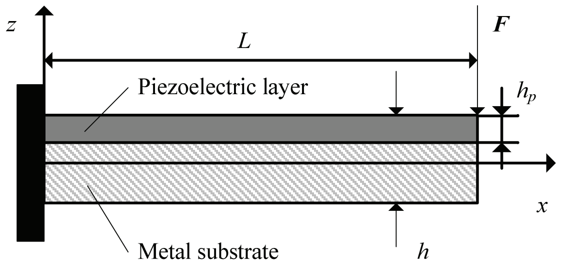
2. Structure and Model

MPG utilizes piezoelectric material deformation enduring external force or displacement to generate charge so as to convert vibration energy in environment to electric energy, and in the specific work environment enhancing generating capacity in finite scale is important because structure size is restricted to volume. So system takes UMG and BMG for research object as shown in Fig. 1, and under outside force or displacement incentive environment, the influence of structural parameters of microcantilever length, width and thickness ratio etc on generating capacity is analyzed to improve generating capacity of UMG and BMG in limited volume. The outline dimensions of UMG and BMG are basically same, only piezoelectric layer thickness of BMG is half of UMG's, and length is l, and width is w, and thickness of Substrate is h_m, and thickness of piezoelectric layer is h_p, and total thickness is h, and adopting subscript u and b represents respectively unimorph and bimorph. On external force or displacement incentive environment, vibration of piezoelectric microcantilever obeys the motion differential equation of Euler-Bernoulli's beam, and generating electric energy obeys the piezoelectric equations, and its boundary conditions are free in mechanical and short in electricity.

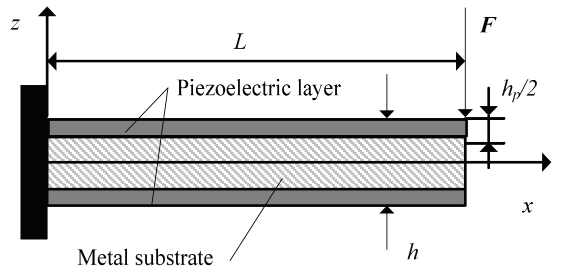
According to piezoelectric theory, the surface of piezoelectric microcantilever generates free charge as its free-end comes into bending deformation enduring external force or displacement. Stress of piezoelectric layer being subjected and electric field of piezoelectric layer generating obeys piezoelectric equations

$$\begin{cases}\{D\}=[d]\{T\}+[\varepsilon^T]\{E\}\\ \{S\}=[s^E]\{T\}+[d]^t\{E\}\end{cases}, \tag{1}$$

where $\{D\}$ is the displacement, $\{E\}$ is the electric field strength, $[d]$ is the piezoelectric constant matrix, $\{S\}$ and $\{T\}$ are the strain and stress respectively, $[\varepsilon^T]$ is the free dielectric constant matrix at stress constant, and $[s^E]$ is the short circuit elastic compliant coefficient matrix at electric field constant.



(a) Unimorph piezoelectric vibration generator.



(b) Bimorph piezoelectric vibration generator.

Fig. 1. Microcantilever of piezoelectric vibration generator.

Let Young's modulus of metal substrate be E_m, Young's modulus of piezoelectric layer be E_p, Poisson's ratio of substrate be μ_m, Poisson's ratio of piezoelectric layer be μ_p, density of substrate be ρ_m, and density of piezoelectric layer be ρ_p. On external force incentive environment, the output voltage u and the electric energy w of piezoelectric microcantilever are as following respectively:

$$\begin{cases}u_m(F)=-\dfrac{3a(1-a)\beta g_{31}l}{A_m wh}F\\ u_b(F)=-\dfrac{3(1-a^2)g_{31}l}{4A_b wh}F\end{cases} \tag{2}$$

$$\begin{cases}w_m(F)=\dfrac{9(1-a)(1-a+a\beta)a^2\beta^2k_{31}^2l^3}{2A_mB_mE_pwh^3}F^2\\ w_b(F)=\dfrac{9(1-a)(1+a)^2k_{31}^2l^3}{2A_bB_bE_pwh^3}F^2\end{cases} \tag{3}$$

On displacement incentive environment, the output voltage u and the electric energy w of piezoelectric microcantilever are as following respectively:

$$\begin{cases} u_m(\delta) = -\dfrac{3a(1-a)\beta g_{31}E_p h^2}{4(1-a+a\beta)l^2}\delta \\ u_b(\delta) = -\dfrac{3(1-a^2)g_{31}E_p h^2}{16l^2}\delta \end{cases} \tag{4}$$

$$\begin{cases} w_m(\delta) = \dfrac{9(1-a)a^2\beta^2 k_{31}^2 E_p A_m W h^3}{32(1-a+a\beta)B_m l^3}\delta^2 \\ w_b(\delta) = \dfrac{9(1-a)(1+a)^2 k_{31}^2 E_p A_b W h^3}{32 B_b l^3}\delta^2 \end{cases} \tag{5}$$

In which,

$$\alpha = h_m / h, \quad \beta = E_m / E_p$$
$$k_{31}^2 = E_p g_{31}^2 / \beta_{33}^T, \quad \beta_{33}^T = 1/\varepsilon_{33}^T, \quad \varepsilon_{33}^T = 3400\varepsilon_0$$
$$A_u = a^4(1-\beta)^2 - 2a(2a^2-3a+2)(1-\beta)+1$$
$$A_b = 1-a^3+a^3\beta$$
$$B_u = A(1-a+a\beta)(1+k_{31}^2) - 3a^2(1-a)\beta^2 k_{31}^2$$
$$B_b = -3(1-a)(1+a)^2 k_{31}^2 + 4A_b(1+k_{31}^2),$$

where g_{31} is the piezoelectric voltage constant, k_{31} is the electromechanical coupling coefficient, α is the thickness ratio, β is the Young's modulus ratio, β_{33}^T is the dielectric isolation ratio, ε_{33}^T is the dielectric constant in z direction, and ε_0 is the vacuum dielectric constant, ε_0=8.85×10^{-12} F/m.

3. Numerical Simulation and Analysis

Finite element analysis software ANSYS is adopted to model and simulate for MPG, and verify further results of mathematics model. Stainless steel with large elastic modulus is selected as substrate for enduring more deformation, and PZT-5H is selected as piezoelectric wafer which has three important parameters with dielectric constant matrix [ε^S], flexibility matrix [s^E] and piezoelectric matrix [e]

$$[\varepsilon^S] = \begin{bmatrix} 1700 & 0 & 0 \\ 0 & 1700 & 0 \\ 0 & 0 & 1470 \end{bmatrix} \times 8.85\times10^{-12}$$

$$[s^E] = \begin{bmatrix} 16.5 & -4.78 & -8.45 & 0 & 0 & 0 \\ 0 & 16.5 & -8.45 & 0 & 0 & 0 \\ 0 & 0 & 20.7 & 0 & 0 & 0 \\ 0 & 0 & 0 & 43.5 & 0 & 0 \\ 0 & 0 & 0 & 0 & 43.5 & 0 \\ 0 & 0 & 0 & 0 & 0 & 42.6 \end{bmatrix} \times 10^{-12}$$

$$[e] = \begin{bmatrix} 0 & 0 & -6.5 \\ 0 & 0 & -6.5 \\ 0 & 0 & 23.3 \\ 0 & 0 & 0 \\ 0 & 17.0 & 0 \\ 17.0 & 0 & 0 \end{bmatrix}$$

Solid5 cell and Solid98 cell are suitable for piezoelectric analysis in ANSYS software, in which Solid5 cell is more suitable for model partition of piezoelectric film, and Solid45 cell is adopted to substrate, and ideal bond between piezoelectric wafer and substrate are supposed, namely displacement and force are continuous of bond layer. Performance parameter of UMG is shown as in Table 1. Relation between structural parameter and output voltage are respectively discussed on 1N external force and 0.1mm displacement incentive environment.

Table 1. The parameters of UMG.

Parameters	Piezoelectric Layer PZT-5H	Stainless Steel Substrate
Density, ρ (kg/m^3)	7600	7900
Young's Modulus, E (GPa)	60.6	206
Poisson's Ratio, μ	0.289	0.3
Coupling Coefficient, k_{31}	0.39	—
Voltage Constant, g_{31}	-9.11×10^{-3}	—
Length, l (mm)	70	70
Width, w (mm)	15	15
Thickness, h (mm)	0.7	1.5

3.1. Length

Currency command flow is compiled for improving efficiency as ANSYS analysis, only the thickness ratios of MPG are varied while other parameters, such as width, thickness ratio, material attribute, etc, are fixed, the relations between output voltage and thickness ratio are obtained as shown in Fig. 2 and Fig. 3.

As is shown in Fig. 2, the output voltage of UMG and BMG increases linearly while the length increases; the output voltage of BMG is higher than of UMG at same length. So, BMG is first selected when vibration energy is collected on external force incentive environment. Moreover, the length should be increased as possible considering the situation of MPG enduring ability.

As is shown in Fig. 3, the output voltage of UMG and BMG decreases while the length increases, and voltage value is inverse ratio to length square; the output voltage of BMG and UMG are basic equal at same length. So, the length of MPG should be decreased as possible when vibration energy is collected on displacement incentive environment.

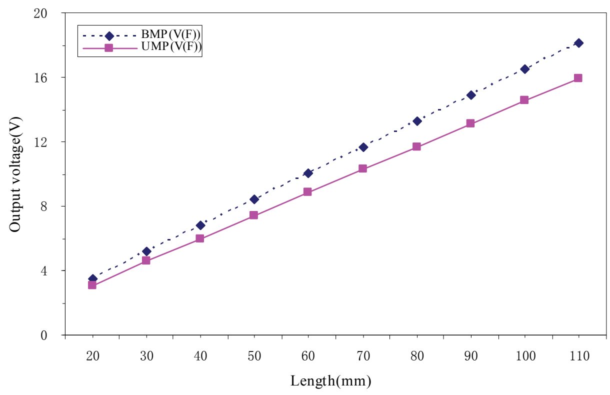


Fig. 2. The output voltage vs. length under external force incentive environment.

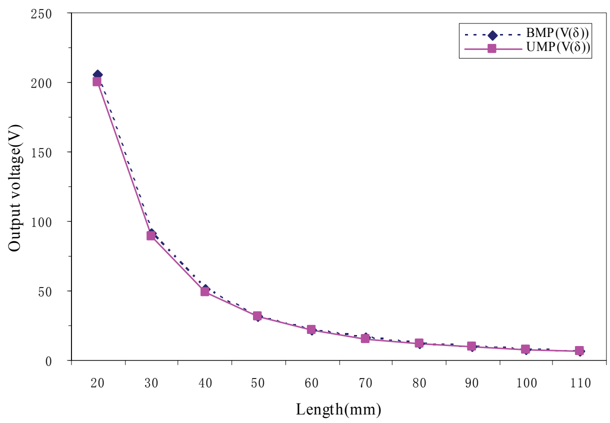


Fig. 3. The output voltage vs. length under displacement incentive environment.

3.2. Width

If MPG parameters, length, thickness ratio and material attribute etc, are fixed, the relation between output voltage and width is obtained by finite element simulation as shown in Fig. 4 and Fig. 5.

As is shown in Fig. 4, the output voltage of UMG and BMG shows inverse proportion decreasing trend while its width increases; the output voltage of BMG is larger than that of UMG at same width. So, BMG is first selected to harvest vibration energy on external force incentive environment. Moreover, width should be decreased as possible considering the situation of MPG enduring ability.

As is shown in Fig. 5, on the displacement incentive environment, output voltage of MPG is not affected by width; output voltage of UMG and BMG are basic equal at same width.

3.3. Thickness Ratio

If the thickness ratios of MPG are only varied while other parameters, such as length, width, material attribute, etc, are fixed, the relation between output voltage and thickness ratio is obtained as shown in Fig. 6.

Influence law of thickness ratio on output voltage are basic same on external force and displacement incentive environment. The UMG output voltage increase at first then decreases with thickness ratio increases. The UMG output voltage occur the maximum at thickness ratio 0.4, which is its optimal thickness ratio. Different from UMG, the output voltage of BMG is decreased with thickness ratio increases, but its maximum output voltage is about three times to UMG. It is obvious that BMG with lower thickness ratio is benefit to enhance generating capacity.

4. Conclusions

For enhancing power supplying ability of WSN, mathematic model of MPG generating capacity are established, and influence law of structural parameter on output voltage of UMG and BMG are analyzed by finite element simulation aiming to external force and displacement incentive environment. The results show that for gaining larger output voltage, on satisfying structural strength and limited dimension range, the structure dimension of MPG should be reasonably determined according special incentive environment. The length of MGP should be increased, and its width should be decreased on external force incentive environment; the length of MGP should be decreased on displacement incentive environment. Moreover, BMG with lower thickness ratio should be selected at first on external force and displacement incentive environment.

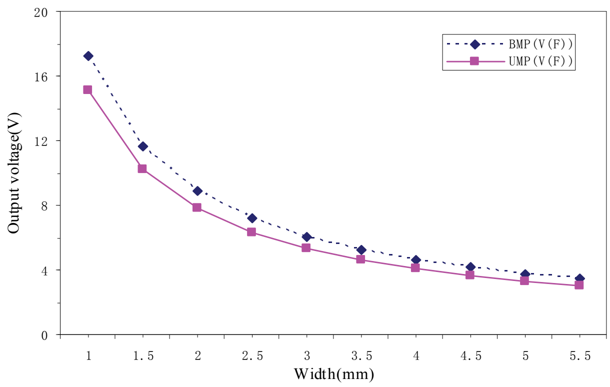


Fig. 4. The output voltage vs. width under external force incentive environment.

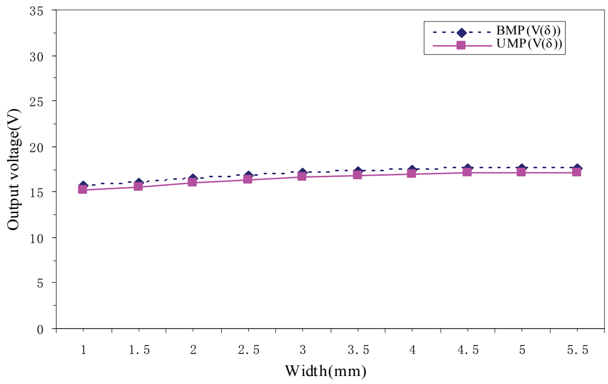
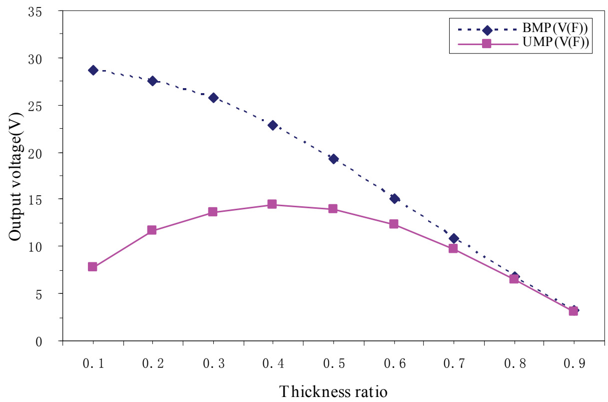
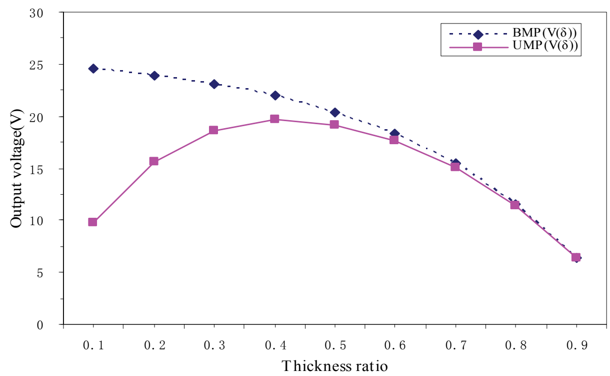


Fig. 5. The output voltage vs. width under displacement incentive environment.



(a) Under external force incentive environment.



(b) Under displacement incentive environment.

Fig. 6. The output voltage vs. thickness ratio.

References

[1]. Wang Y. S., Chen N. F., Zhang X. W., et al. Analysis of leakage current in gas micro-solar cell arrays, *Science China-Technological Sciences*, 53, 5, 2010, pp. 1240- 1246.

[2]. G. Overton, Semiconductor lasers: Curved grating creates high-brightness surface- emitting DFB laser, *Laser Focus World*, 45, 4, 2009, p. 36.

[3]. N. Matsui, F. Kurokawa, and K. Shiraishi, A new accurate model for waste heat recovery system using power turbine generator: A new approach to shipboard energy system, *IEEJ Transactions on Electrical and Electronic Engineering,* 5, 6, 2010, pp. 717-723.

[4]. A. H. Mazinan, and N. Sadati, Fuzzy predictive control based multiple models strategy for a tubular heat exchanger system, *Applied Intelligence*, 33, 3, 2010, pp. 247-263.

[5]. Z. J. Chew, and L. J. Li, Design and characterization of a piezoelectric scavenging device with multiple resonant frequencies, *Sensors Actuators A: Physical,* 162, 1, 2010, pp. 82-92.

[6]. L. Patel, E. Siores, and T. Shah, Utilisation of smart polymers and ceramic based piezoelectric materials for scavenging wasted energy, *Sensors Actuators A: Physical,* 159, 2, 2010, pp. 213-218.

[7]. C. R. Saha, T. O. Donnell, N. Wang, and P. McCloskey, Electromagnetic generator for harvesting energy from human motion, *Sensors Actuators A: Physical,* 147, 2008, pp. 248-253.

[8]. B. P. Mann, and N. D. Sims, Energy harvesting from the nonlinear oscillations of magnetic levitation, *Journal of Sound and Vibration*, 319, 2009, pp. 515-530.

[9]. P. H. Wang, K. Tanaka, S. Sugiyama, X. H. Dai, X. L. Zhao, and J. Q. Liu, A micro electromagnetic low level vibration energy harvester based on MEMS technology, *Microsystem Technologies,* 15, 6, 2009, pp. 941-951.

[10]. R. Torah, P. Glynne-Jones, and M. Tudor, T. O'Donnell, S Roy, and S Beeby, Self-powered autonomous wireless sensor node using vibration energy harvesting, *Measurement Science and Technology,* 19, 12, 2008, 125202.

[11]. P. D. Mitcheson, P. Miao, B. H. Stark, E. M. Yeatman, A. S. Holmes, and T. C, Green, MEMS electrostatic micropower generator for low frequency operation, *Sensors and Actuators A: Physical,* 115, 2-3, 2004, pp. 523-529.

[12]. P. Glynne-Jones, M. J. Tudor, S. P. Beeby, and N. M. White, An electromagnetic, vibration-powered generator for intelligent sensor systems, *Sensors and Actuators A: Physical,* 110, 1-3, 2004, pp. 344-349.

[13]. C. A. Howells, Piezoelectric energy harvesting, *Energy Conversion and Management*, 50, 7, 2009, pp. 1847-1850.

[14]. J. R. Liang, and W. H. Liao, Piezoelectric Energy Harvesting and Dissipation on Structural Damping, *Journal of Intelligent Material Systems and Structures*, 20, 5, 2009, pp. 515-527.

[15]. E. K. Reilly, and P. K. Wright, Modeling, fabrication and stress compensation of an epitaxial thin film piezoelectric microscale energy scavenging device, *Journal of Micromechanics and Microengineering*, 19, 2009, 095014.

[16]. H. A. Sodano, D. J. Inman, and G. Park, A review of power harvesting from vibration using piezoelectric materials, *The Shock and Vibration Digest*, 36, 3, 2004, pp. 197-205.

[17]. L. F. Lou, Y. T. Yang, Y. J. Li, and J. Q. Zhang, Dynamic analysis of piezoelectric thin film microsensor, *Machine Design and Research*, 21, 3, 2005, pp. 65-67.

[18]. J. W. Kan, K. H. Tang, S. Y. Wang, Z. G. Yang, J. Jia, and P. Zeng, Modeling and simulation of piezoelectric cantilever generators, *Optics and Precision Engineering,* 16, 1, 2008, pp. 71-75.

[19]. J. B. Yuan, X. T. Shan, T. Xie, and W. S. Chen, Experiment of monocrystal piezoelectric generator with cantilever beam structure, *Optics and Precision Engineering,* 17, 5, 2009, pp. 1072-1077.