JCAMECH

Vol. 47, No. 2, December 2016, pp 241-246
DOI: 10.22059/jcamech.2017.224952.125

Studying piezoelastic and piezomagnetoelastic configurations for different excitation frequencies in MEMS energy harvesters

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Received: 10 Sep. 2016 , Accepted: 19 Dec. 2016

Abstract

Typically two configurations are used for energy harvesting with different advantages: piezoelastic and piezomagnetoelastic. Best performance of the piezoelastic configuration is when the excitation frequency is close to the resonance frequency. If the input frequency slightly deviates from the natural frequency, the generated power is severely decreased. To tackle the problem, the piezomagnetoelastic configuration has been introduced. This configuration can be used near the non-resonant frequencies. This paper examines the effects of frequency and damping in the two above-mentioned configurations. The results of the study indicate that with increasing the damping, the harvested energy decreases. Also the results show that at higher frequencies, piezomagnetoelastic operation is better than the piezoelastic one; but at low frequencies, piezoelastic configuration is the better option.

Keywords: *Piezoelastic, Piezomagnetoelastic, Energy harvesting*

10. Introduction

Nowadays, energy harvesting is one of the most interesting topics in MEMS research and industry. Researchers are trying to increase the power generation for the low-power devices using environmental sources. The idea of energy harvesting from ambient vibrations to generate voltage is a favorite field over the past decade, specially using MEMS Devices. To generate power for such devices (e.g. networks of wireless sensors used in monitoring applications), the mechanical energy is converted to output voltage using a piezoelectric material.

Power generation from human motion during walking and running has been studied in some studies [1, 2]. Several researchers have worked on applications and modeling of energy harvesting from ambient vibrations using piezoelectric [3], electromagnetic [4], electrostatic [5, 6], and magnetostrictive [7] mechanisms. In energy harvesting, piezoelectric materials are the most popular ones due to their high power capacties, structural adapting capability, feasibility of fabrication in micro-scale [8-10] and ease of the application. The effects of piezoelectric nonlinearity have been examined in energy harvesting in Refs. [11, 12]. With the increase in the nonlinearity, the operation effectiveness decreases. The simulations have shown that the chaotic behavior of piezoelastic configuration increases the power generation [13, 14]. The piezomagnetoelastic configuration has also been examined in Gaussian white noise excitation [12]. Generally, the piezoelectric energy harvesters are made with piezoceramic layers integrated on a beam for energy harvesting from ambient vibration. However, for acceptable power generation, the energy harvesting is limited to work in excitation frequencies

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near the resonance frequency. If the input frequency slightly deviates from the configuration resonance frequency, the electrical power output is severely reduced [15]. Equations and phase portraits of the piezoelastic and the piezomagnetoelastic configurations have been compared theoretically and the advantage of each one have been studied in Ref. [15].

Mechanical vibration is a potential power source which is easily converted to electrical energy using (MEMS) technology [21]. Therefore, MEMS Energy harvesting is very popular nowadays [21]. For further study on MEMS and MEMS Energy harvesting, pls see [22-30] and [31-33] respectively.

In the past researches, the operation of both piezoelastic and piezomagnetoelastic configurations have not been studied in low frequencies.

In the present study, we investigate the effects of dimensionless input frequency and dimensionless damping parameters for both of piezoelastic and piezomagnetoelastic configurations.

The contents of the paper are as follows: the modeling of different configurations is presented in Section 2, the results are discussed in Section 3, and finally, Section 4 concludes the paper.

11. Modeling

11.1. *Dynamic equations of piezoelectric configuration:*

Dynamic equation of the magnetoelastic configuration has been studied by Moon and Holmes before [16]. This configuration consists of a ferromagnetic beam that two permanent magnets located symmetrically close to the beam end and the external excitation is applied. The governing dynamic equation of motion has the famous form of the bistable Duffing equation [16-18].

In the magnetoelastic configuration, two piezoceramic layers are integrated over the surface of the cantilever and therefore a bimorph is constructed, which is shown in Fig. 1.

Motion equations of the nonlinear system are as follow:

$$\ddot{w} + 2cz\dot{w} - \frac{1}{2}\mathrm{w}(1-w) - \alpha\upsilon = A\cos(\omega t) \tag{1}$$

$$\dot{\upsilon} + \beta\upsilon + \gamma\dot{x} = 0 \tag{2}$$

where w is the dimensionless displacement of the cantilever tip in the transverse direction, υ is the dimensionless voltage generated by piezoelectric strain, c is the factor of mechanical damping, ω is the dimensionless input frequency, A is the dimensionless applied input due to base motion ($A \propto \omega^2 A_0$, where A_0 is the dimensionless amplitude of the base deflection), α is the dimensionless coupling coefficient of piezoelectric in the motion equation, γ is the dimensionless coupling coefficient of the piezoelectricity in the electrical equation, β is the dimensionless time constant ($\beta \propto \frac{1}{R_l C_p}$, where R_l is the resistance of load and C_p is the equivalent capacitance of the piezoceramic layers), and dot indicates differentiation with respect to the dimensionless time. It should be noted that the inherent nonlinearity of the piezoelectricity [19, 20] is neglected in Eqs. 1 and 2 by supposing the linear behavior for used piezoelectric material [15].

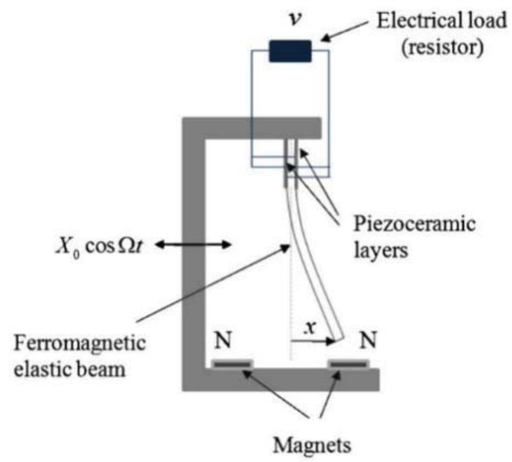


Fig. 1. The magnetoelastic configuration

Eqs. 1 and 2 are represented as the state-space form:

$$\begin{Bmatrix} \dot{u}_1 \\ \dot{u}_2 \\ \dot{u}_3 \end{Bmatrix} = \begin{Bmatrix} u_2 \\ -2cu_2 + \frac{1}{2}u_1(1-u_1{}^2) + \alpha u_3 + A\cos(\omega t) \\ -\beta u_3 - \gamma u_2 \end{Bmatrix} \tag{3}$$

where the state variables are $u_1 = w$, $u_2 = \dot{w}$ and $u_3 = \upsilon$. The coupled motion equations obtained by Eq. (3) can be converted to the state-space form (the ode45 command of MATLAB is applied for the equations).

11.2. *Dynamic equations of piezomagnetoelastic configuration:*

Motion equation of the piezomagnetoelastic configuration is described as follow:

$$\ddot{w} + 2c\dot{w} + \frac{1}{2}w - \alpha\upsilon = A\cos(\omega t) \qquad (4)$$

$$\dot{\upsilon} + \beta\upsilon + \gamma\dot{w} = 0 \qquad (5)$$

which can be introduced in the state-space form as

$$\begin{Bmatrix} \dot{u}_1 \\ \dot{u}_2 \\ \dot{u}_3 \end{Bmatrix} = \begin{Bmatrix} u_2 \\ -2cu_2 - \frac{1}{2}u_1 + \alpha u_3 + A\cos(\omega t) \\ -\beta u_3 - \gamma u_2 \end{Bmatrix} \qquad (6)$$

12. Results and discussion

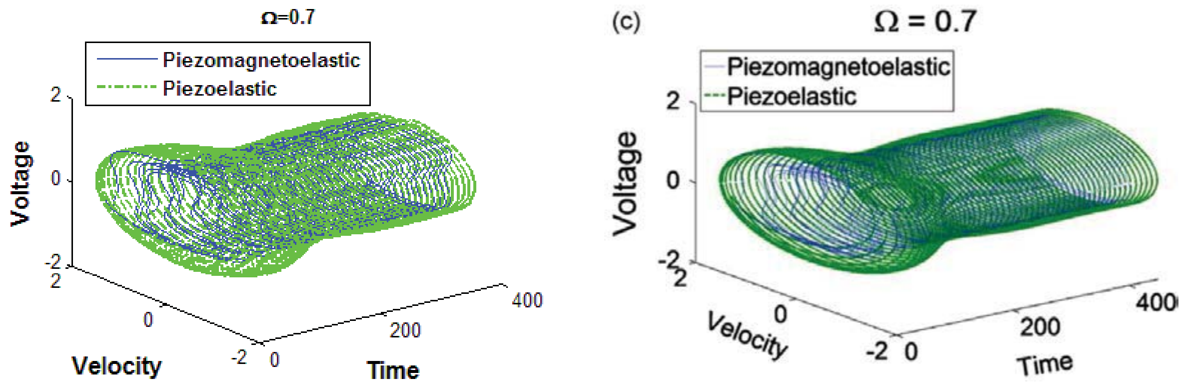
In conventional configurations, most of the harvested energy is obtained near the resonant frequency. To solve this problem, piezomagnetoelastic configuration is introduced. This configuration uses two magnets in the tip of the beam to make large deflections in high frequencies. This concept changes the motion equation of piezoelastic configuration and improves the performance of the conventional configuration in higher frequencies. However, at low frequencies, the piezomagnetoelastic configuration is not suitable, because the harvested energy largely decreases. In Ref. [15], the appropriate parameters for both piezoelastic and piezomagnetoelastic configurations has been mentioned. In our study, the same parameters are assumed. The parameters are:

$\zeta = 0.01, \chi = 0.05, \kappa = 0.5$

Initial conditions and the input amplitude are:

$f = 0.08, x(0) = 1, \dot{x}(0) = 1.3$

In this paper, effects of input frequency in two configurations are investigated. To validate the model, the obtained results are compared with the results in Ref. [15]. Comparing the results shows that our model is in good agreement with the previous models (see Fig.3 and Fig.4). Figs. 2 and 3 indicate that the piezomagnetoelastic configuration has a better performance rather than the piezoelastic configuration in higher dimensionless frequencies.



(a) (b)

Fig. 2. 3D Voltage-Velocity-Time diagrams for two configurations a)Our results b) Results in Ref. [15] (dimensionless input frequency is 0.7)

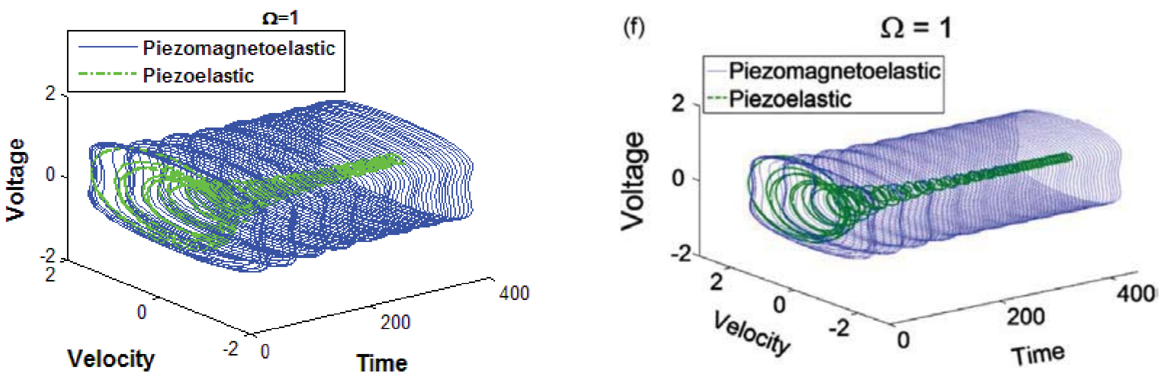
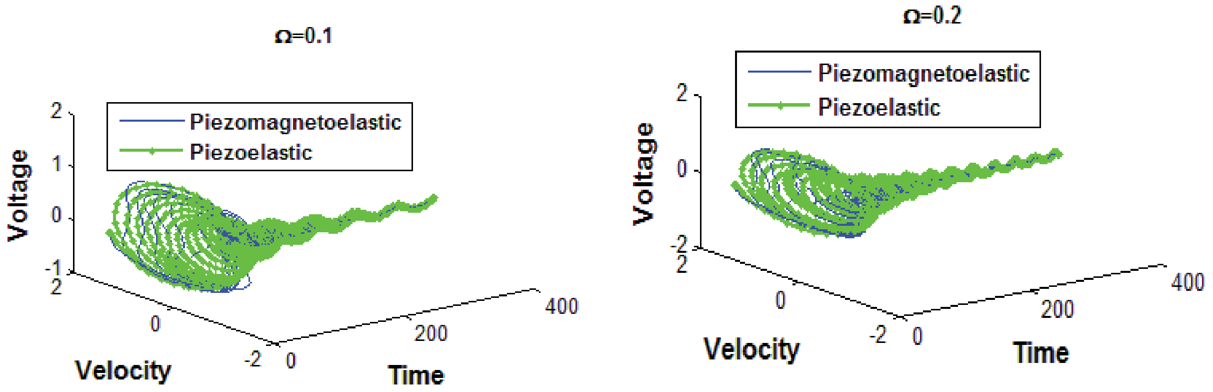


Fig. 3. 3D Voltage-Velocity-Time diagrams for two configurations a)Our results b) Results in Ref. [15] (dimensionless input frequency is 1.0)

In the next step, the performance of piezoelastic and piezomagnetoelastic configurations is investigated in the lower dimensionless excitation frequencies. Fig.4 shows that the piezoelastic configuration generates more power rather than the piezomagnetoelastic configuration in lower excitation frequencies. Therefore, for the lower input frequencies, it is recommended to use the piezoelastic configuration; the configuration also has an easier fabrication method and more power generation in comparison with piezomagnetoelastic configuration.



(a)

(b)

Fig. 4. 3D Voltage-Velocity-Time diagrams for two configurations a) $\Omega = 0.1$ and b) $\Omega = 0.2$

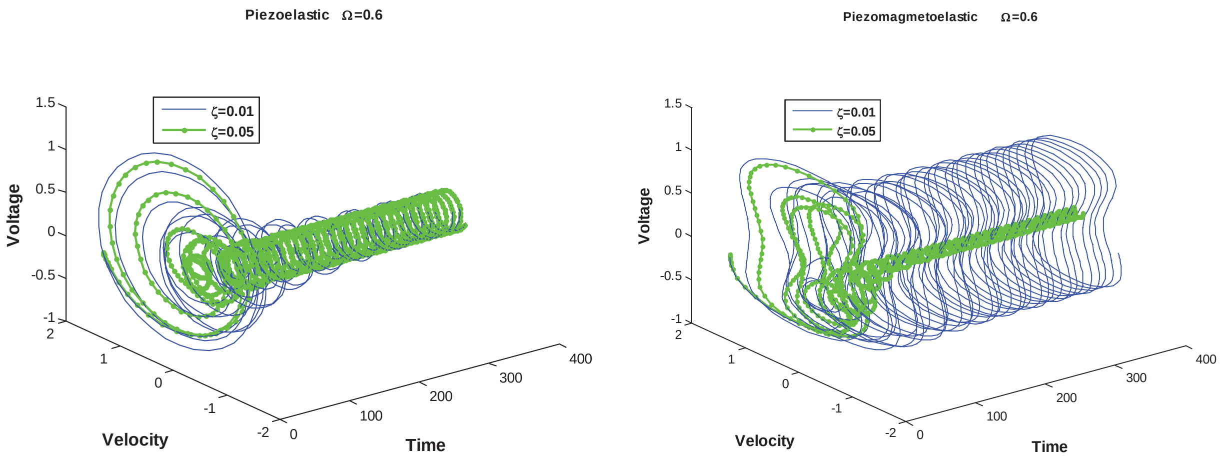
The damping is an important parameter for energy harvesting that can cause increasing or decreasing the harvested energy. Here, we also examine the two aforementioned configurations in the different dimensionless damping parameters. The results presented in Fig. 5, show the piezomagnetoelastic configuration is more sensitive to damping parameters change. Fig. 5 indicates that increasing the dimensionless damping parameter decrease the generated power in both configurations. However, it is clear that the reduction of the harvested energy in piezoelastic configuration is fewer rather than the other one.

13. Conclusions

In this study, effects of damping and input frequency on energy harvesting in piezoelastic and piezomagnetoelastic configurations were investigated. The results indicated that the configuration of piezomagnetoelastic has a good performance for the higher dimensionless input frequencies, but the performance is poor in the lower excitation frequencies.

In low excitation frequencies, piezoelastic configuration is a better choice with respect to the other configuration due to the easy fabrication process and its better performance.

The investigations of damping effect indicated that increasing the dimensionless damping factor decreases the power generation. The decrease amount in the piezomagnetoelastic configuration is large, while that amount is smaller in the piezoelastic configuration. It means that piezomagnetoelastic configuration is very sensitive to the changes in damping parameter. Therefore the configuration is not appropriate for usage in higher damping parameter.



(a) (b)

Fig. 5. 3D Voltage-Velocity-Time diagrams for two configurations a) $\zeta = 0.01$ and b) $\zeta = 0.05$

References

[1] J. Cao, W. Wang, S. Zhou, D. J. Inman, and J. Lin, "Nonlinear time-varying potential bistable energy harvesting from human motion," Applied Physics Letters, vol. 107, p. 143904, 2015.

[2] J.-P. Martin and Q. Li, "Overground vs. treadmill walking on biomechanical energy harvesting: An energetics and EMG study," Gait & Posture, vol. 52, pp. 124-128, 2017.

[3] M. Lallart, "Nonlinear technique and self-powered circuit for efficient piezoelectric energy harvesting under unloaded cases," Energy Conversion and Management, vol. 133, pp. 444-457, 2017.

[4] 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, vol. 110, pp. 344-349, 2004.

[5] S. Roundy, P. K. Wright, and J. Rabaey, "A study of low level vibrations as a power source for wireless sensor nodes," Computer communications, vol. 26, pp. 1131-1144, 2003.

[6] S. Roundy and P. K. Wright, "A piezoelectric vibration based generator for wireless electronics," Smart Materials and structures, vol. 13, p. 1131, 2004.

[7] D. Davino, P. Krejčí, A. Pimenov, D. Rachinskii, and C. Visone, "Analysis of an operator-differential model for magnetostrictive energy harvesting," Communications in Nonlinear Science and Numerical Simulation, vol. 39, pp. 504-519, 2016.

[8] S. R. Anton and H. A. Sodano, "A review of power harvesting using piezoelectric materials (2003–2006)," Smart materials and Structures, vol. 16, p. R1, 2007.

[9] S. Priya, "Advances in energy harvesting using low profile piezoelectric transducers," Journal of electroceramics, vol. 19, pp. 167-184, 2007.

[10] H. A. Sodano, D. J. Inman, and G. Park, "A review of power harvesting from vibration using piezoelectric materials," Shock and Vibration Digest, vol. 36, pp. 197-206, 2004.

[11] M. A. Savi, "Nonlinear dynamics of a vibration-based duffing-type energy harvesting system using piezoelectric materials," 2013.

[12] P. Kumar, S. Narayanan, S. Adhikari, and M. Friswell, "Fokker–Planck equation analysis of randomly excited nonlinear energy harvester," Journal of Sound and Vibration, vol. 333, pp. 2040-2053, 2014.

[13] S. C. Stanton and B. P. Mann, "Engaging nonlinearity for enhanced vibratory energy harvesting," in 51st AIAA/ASME/ASCE/AHS/ASC Structures, Structural Dynamics, and Materials Conference 18th AIAA/ASME/AHS Adaptive Structures Conference 12th, 2010, p. 3067.

[14] K. Remick, D. D. Quinn, D. M. McFarland, L. Bergman, and A. Vakakis, "High-frequency vibration energy harvesting from impulsive excitation utilizing intentional dynamic instability caused by strong nonlinearity," Journal of Sound and Vibration, vol. 370, pp. 259-279, 2016.

[15] A. Erturk and D. Inman, "Broadband piezoelectric power generation on high-energy orbits of the bistable Duffing oscillator with electromechanical coupling," Journal of Sound and Vibration, vol. 330, pp. 2339-2353, 2011.

[16] F. Moon and P. J. Holmes, "A magnetoelastic strange attractor," Journal of Sound and Vibration, vol. 65, pp. 275-296, 1979.

[17] J. Guckenheimer and P. Holmes, Nonlinear oscillations, dynamical systems, and bifurcations of vector fields vol. 42: Springer Science & Business Media, 1983.

[18] P. Holmes, "A nonlinear oscillator with a strange attractor," Philosophical Transactions of the Royal Society of London A: Mathematical, Physical and Engineering Sciences, vol. 292, pp. 419-448, 1979.

[19] A. Triplett and D. D. Quinn, "The effect of non-linear piezoelectric coupling on vibration-based energy harvesting," Journal of Intelligent Material Systems and Structures, vol. 20, pp. 1959-1967, 2009.

[20] S. C. Stanton, A. Erturk, B. P. Mann, and D. J. Inman, "Nonlinear piezoelectricity in electroelastic energy harvesters: modeling and experimental identification," Journal of Applied Physics, vol. 108, p. 074903, 2010.

[21] Jeon, Y. B., R. Sood, J-H. Jeong, and S-G. Kim, "MEMS power generator with transverse mode thin film PZT," Sensors and Actuators A: Physical, vol. 122, no. 1, pp. 16-22, 2005.

[22] M. Mojahedi, M. Moghimi Zand, M. T. Ahmadian, "Static pull-in analysis of electrostatically actuated microbeams using homotopy perturbation method", Applied Mathematical Modelling 34, no. 4, pp: 1032-1041, 2010.

[23] H. Daneshpajooh, M. Moghimi Zand, "Semi-analytic solutions to oscillatory behavior of initially curved micro/nano systems", Journal of Mechanical Science and Technology 29, no. 9, pp: 3855-3863, 2015.

[24] M. Mojahedi, M. Moghimi Zand, M. T. Ahmadian, M. Babaei, "Analytic solutions to the oscillatory behavior and primary resonance of electrostatically actuated microbridges", International Journal of Structural Stability and Dynamics 11, no. 06, pp: 1119-1137, 2011.

[25] M. Moghimi Zand, "The dynamic pull-in instability and snap-through behavior of initially curved microbeams." Mechanics of Advanced Materials and Structures 19, no. 6, pp: 485-491, 2012.

[26] M. Moghimi Zand, A. Ostadi Moghaddam, "Pull-in instability and vibrations of a beam micro-gyroscope", Journal of Computational Applied Mechanics 45, no. 1, pp: 29-34, 2014.

[27] M. Mojahedi, M. Moghimi Zand, M. T. Ahmadian, "Investigation of the oscillatory behavior of electrostatically-actuated microbeams", ASME 2010 International Mechanical Engineering Congress and Exposition, pp. 619-626. American Society of Mechanical Engineers, 2010.

[28] I. Isaac Hosseini, M. Moghimi Zand, M. Lotfi, "Dynamic pull-in and snap-through behavior in micro/nano mechanical memories considering squeeze film damping", Microsystem Technologies, pp: 1-10, 2016.

[29] M. Moghimi Zand, B. Rashidian, M. T. Ahmadian, "Contact time study of electrostatically actuated microsystems", Scientia Iranica. Transaction B, Mechanical Engineering 17, no. 5 vol. 348, 2010.

[30] M. Moghimi Zand, M. T. Ahmadian, "Characterization of coupled-domain multi-layer microplates in pull-in phenomenon, vibrations and dynamics", International Journal of Mechanical Sciences 49, no. 11, pp: 1226-1237, 2007.

[31] Fang, Hua-Bin, Jing-Quan Liu, Zheng-Yi Xu, Lu Dong, Li Wang, Di Chen, Bing-Chu Cai, and Yue Liu. "Fabrication and performance of MEMS-based piezoelectric power generator for vibration energy harvesting." Microelectronics Journal, vol. 37, no. 11, pp: 1280-1284, 2006.

[32] Liu, Jing-Quan, Hua-Bin Fang, Zheng-Yi Xu, Xin-Hui Mao, Xiu-Cheng Shen, Di Chen, Hang Liao, and Bing-Chu Cai. "A MEMS-based piezoelectric power generator array for vibration energy harvesting." Microelectronics Journal, vol. 39, no. 5, pp: 802-806, 2008.

[33] P. Muralt, M. Marzencki, B. Belgacem, F. Calame, and S. Basrour. "Vibration energy harvesting with PZT micro device." Procedia Chemistry, vol. 1, no. 1, pp: 1191-1194, 2009.