International Journal of Mechanical, Industrial and Aerospace Sciences
ISSN: 2517-9950
Vol:14, No:4, 2020

Effect of Damping on Performance of Magnetostrictive Vibration Energy Harvester

Mojtaba Ghodsi, Hamidreza Ziaifar, Morteza Mohammadzaheri, Payam Soltani

Abstract**—**This article presents an analytical model to estimate the harvested power from a Magnetostrictive cantilevered beam with tip excitation. Furthermore, the effects of internal and external damping on harvested power are investigated. The magnetostrictive material in this harvester is Galfenol. In comparison to other popular smart materials like Terfenol-D, Galfenol has higher strength and machinability. In this article, first, a mechanical model of the Euler-Bernoulli beam is employed to calculate the deflection of the harvester. Then, the magneto-mechanical equation of Galfenol is combined with Faraday's law to calculate the generated voltage of the Magnetostrictive cantilevered beam harvester. Finally, the beam model is incorporated in the aforementioned combination. The results show that a 30×8.5×1 mm Galfenol cantilever beam harvester with 80 turn pickup coil can generate up to 3.7 mV and 9 μW. Furthermore, sensitivity analysis made by Response Surface Method (RSM) shows that the harvested power is only sensitive to the internal damping coefficient.

Keywords**—**Internal damping coefficient, external damping coefficient, Euler-Bernoulli, energy harvester, Galfenol, magnetostrictive, response surface method.

I. Introduction

NOWADAYS mechanical energy harvesters play a significant role in a wide range of applications from health monitoring systems in mechanical structures to pacemaker implants in human bodies. Although it seems that the generated power by these vibrational harvesters is very low, this amount of energy is enough to energize a low power system such as health monitoring systems of mechanical, civil and aerospace structures or any other wireless sensor networks. Usually electromagnetic [1]-[4] conversion system is suitable for generating from mW to Watt power level. Furthermore, electrostatics [5]-[7] technique is employed for MEMS applications to generate in the microwatt power level. Among all, the use of smart materials is on the rise. Smart materials have wide applications in actuators [8]-[15], sensors [16], and harvesters [17], [18]. Although hysteresis [19], creep [20] and presence of Eddy current [21] complicate the modeling process for smart-material-based harvesters, these harvesters have a wide range of working frequency and can be used in relatively small spaces [22], [23]. The most common material used in energy harvesting is piezoelectric (PZT) [24], [25]. Although PZT harvesters are suitable for wide frequency bandwidth, their poor electro-mechanical coupling coefficient and brittleness of PZT makes these materials unreliable for long life operation [26]-[30]. In contrast to PZT, magnetostrictive materials have high stiffness and high magneto-mechanical coupling coefficient [9], [31], [32]. These merits make them suitable for long-life harvesters that operate with high efficiency in a wide range of temperatures [33]. Energy harvesters are usually classified as force driven or velocity driven. Both consist of an active material and a pickup coil. In force driven harvesters, a rod, made of the active material, is under normal stress, and in velocity driven harvesters, a cantilevered beam, made of the active material, is under lateral bending. Based on the Villari effect, when the rod is under normal stress (force driven) or lateral bending (velocity driven), its magnetization changes induce a voltage in the pickup coil. Conventionally, the velocity driven harvesters are made of PZT and they are excited from the base. Analytical models presented for these harvesters normally neglect both internal and external damping [34]-[37].

In this article, a mechanical model for velocity driven harvester, made of Galfenol, is proposed. Galfenol is an iron-gallium alloy and is a suitable choice for use in actuators, energy harvesters, sonar systems, and active vibration control system. In comparison to PZT, Galfenol has higher Young's modulus (~70 GPa), higher relative magnetic permeability (60~300) and higher machinability. In the proposed model an external force can be applied at any point of the beam, not only the base. Moreover, this model considers both internal and external damping of the beam. In the second section, the developed mechanical model is combined with analytical solutions to relevant magneto-mechanical coupling and magnetics governing equations. The resultant holistic model can estimate voltage and power generated in the proposed harvester for different forces applied on different points of the harvester beam. In the end, deflection of the beam as well as maximum voltage and power generated by the proposed harvester are calculated under resonant conditions. Results indicate a significant influence of internal damping on harvester performance.

II. Mechanical Model of Cantilever Beam Harvester

A magnetostrictive cantilevered harvester consists of an active material fixed in one end and free in the other end, surrounded by a pickup coil. The fixed end of the beam is located on a solid base that has no movement. The pickup coil is connected to an external resistor load that its voltage is

Mojtaba Ghodsi was with Sultan Qaboos University. He is now with the School of Energy and Electronic Engineering, University of Portsmouth, UK (corresponding author, phone: +44 (0) 23 9284 2674; e-mail: Mojtaba.ghodsi@port.ac.uk)
Hamidreza Ziaiefar and Morteza Mohammadzaheri are with Mechanical and Industrial Engineering Department, Sultan Qaboos University, P.O.Box 33, Alkhoud, Seeb, Muscat, Oman.
Payam Soltani is with School of Mechanical, Aerospace and Automatic Engineering, Coventry University, UK.

measured. This article particularly concentrates on the mechanical aspects of the energy harvester and does not investigate the difference between configurations of electrical load. The harvester beam is realistically considered as a uniform Euler-Bernoulli beam, which has only vertical transverse vibration. In contrast to most of the cantilevered harvesters, in this one, the base has no vibration and the external force can be applied to any point of the beam. The applied force generates a moment on the magnetostrictive rod. Two damping factors are separately considered in this research. The first damping factor that is influenced by the surrounding environment is called external (r_{ext}). The second one related to the internal friction of material is called internal damping (r_{int}). Considering these damping factors, the absolute displacement of the beam can be written as [18].

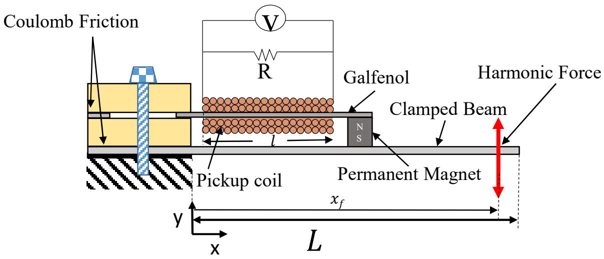

Fig. 1 Schematic view of Galfenol harvester

$$EI\frac{\partial^4 v(x,t)}{\partial x^4} + U\frac{\partial^2 v(x,t)}{\partial t^2} + r_{ext}\frac{\partial v(x,t)}{\partial t} + r_{int}\frac{\partial^5 v(x,t)}{\partial x^4 \partial t} = p(x,t) \tag{1}$$

where $v(x,t)$ is the displacement of the beam at point x in y-direction at time t, E is Young's modulus, I is the moment of inertia of the cross-section and $p(x,t)$ is the applied force to the beam. U is the effective mass of the harvester. The applied oscillating force to the harvester is harmonic. Hence, it can be modelled as:

$$p(x,t) = F_0\, e^{j\omega t}\delta(x - x_f) \tag{2}$$

where F_0 is the amplitude of the oscillating force, ω is the frequency of the applied force, x_f is the position of applied harmonic force and j is the imaginary unit or $\sqrt{-1}$.

Since the damping factors are considered in (1), the displacement of the beam, v, was considered to be complex. Therefore, (1) can be written as:

$$EI\frac{\partial^4 w(x,t)}{\partial x^4} + \mu\frac{\partial^2 w(x,t)}{\partial t^2} + r_{ext}\frac{\partial w(x,t)}{\partial t} + r_{int}\frac{\partial^5 w(x,t)}{\partial x^4 \partial t} = F_0\, e^{j\omega t}\delta(x - x_f) \tag{3}$$

where v(x,t)=Re{w(x)}. Equation (3) is partial differential and the solution can be assumed as

$$w(x,t) = X(x)T(t) = X(x)e^{j\omega t} \tag{4}$$

By substituting (4) in (3):

$$\frac{\partial^4 X(x)}{\partial x^4} + \frac{(\mu\omega^2 - j r_{ext}\omega)}{(EI + j r_{int}\omega)}X = \frac{F_0\delta(x - x_f)}{(EI + j r_{int}\omega)} \tag{5}$$

As shown in [18] by solving (5), displacement can be found. Furthermore, the resonance frequency of the cantilever beam, in which the harvester shows maximum performance at it, can be determined.

III. Magneto-Mechanical Coupling of Galfenol

The goal of this section is to find a relationship to estimate generated voltage in the energy harvester. By applying transverse harmonic force to the cantilevered beam, Galfenol as a part of the beam would be subject to tensile and compressive bending stresses. As a result, the flux inside of the Galfenol would repeatedly changes and based on Faraday's law, voltage would be generated within the pickup coil shown in Fig. 1. The coil surrounds the active part of the Galfenol and is connected to an external resistor as a load. By assuming the vibration as a transverse harmonic force, the magneto-mechanical relation of Galfenol can be linearized as

$$\begin{cases} B = \mu^\sigma H + d^*\sigma \\ \varepsilon = dH + \frac{\sigma}{E} \end{cases} \tag{6}$$

where B and H are magnetic flux density and magnetic field, respectively, σ and ε are applied stress and strain. μ^σ is the magnetic permeability in constant mechanical stress. d and d^* are two magnetostrictive coefficients and can be described as [38]:

$$\begin{cases} d = \left.\frac{\partial \varepsilon}{\partial H}\right|_\sigma \\ d^* = \left.\frac{\partial B}{\partial \sigma}\right|_H \end{cases} \tag{7}$$

where d and $d^*$are measured at constant stress and strain, respectively and are considered to be equal. As proved in [18], the generated voltage across the external resistive load R, can be calculated from (10).

$$\begin{gathered} v\,(t) = \frac{G_2}{1 + j\omega G_1}\left(e^{-j\omega t} - e^{\frac{-t}{G_1}}\right) \\ G1 = \frac{N^2 RA\mu}{l} \\ G2 = \frac{j\omega NAdEy}{l}X(x) \end{gathered} \tag{8}$$

where N and l are the number of turns and length of the pickup coil, respectively. Furthermore, A and E are the cross-section area and Young's modulus of the Galfenol. In addition, ω is the excitation frequency of the harvester while z is the distance between the centroid of the cross-section of Galfenol and neutral axes. The value of R is equal to the total resistance of the circuit. Considering the coil has negligible resistance, R is almost equal to external resistance parallel to the harvester. Using (8), the effect of both r_{ext} and r_{int}, on resonance frequency, generated voltage and power of the cantilevered harvester are shown in Figs. 2-4. In these figures, the external load has been changed from 0 to 10 Ω and the harmonic force amplitude is 0.106 N at the tip of the harvester. The harvested voltage and power are calculated at the resonance frequency. Other related parameters are shown in Table I. The resonance frequency (Fig. 2) varies from 173 to 177 Hz for different damping coefficients. As shown in Fig. 3, the generated voltage of the beam with damping almost saturates around 3.7 mV. Moreover, the highest generated power of the harvester happens with a 0.8 Ω external resistor which is about to 9 µW.

IV. Sensitive Analysis of Damping Coefficient

Based on the results show in Figs. 2-4, the external and internal damping coefficients seem to be effective on the output harvested power. To investigate this assumption, design of experiments (DOE) was employed. The aim of this section is to find optimum operating conditions while the internal and external coefficients are assumed adjustable. The variable factors in this harvester are r_{ext} and r_{int}. To maximize the harvested power, the RSM was used to find proper values for each factor to have maximum power. To find a regression equation between the harvested power and damping coefficients, Minitab 17 software was employed. As shown in Table II, two factors with five levels were considered. Based on the design proposed by RSM and selection of $\alpha = 1.44$, it was found that nine simulation results including one center point is required (Table III). Table IV shows the P_{value} and the coefficients of each factor. Since the P_{value} of r_{ext} is greater than 0.05, external damping has a negligible effect on the output power. However, r_{int} is effective, since its P_{value} is smaller than 0.05. R-Sq = 99.9% shows the goodness of the model represented by RSM.

TABLE I
HARVESTER PARAMETERS

Terms	Values
Cross-section of Galfenol, *A*	8.5 (mm^2)
Young Modolues, *E*	72 (GPa)
Galfenol density, ρ	7970 (kg/m^3)
Magnetostriction coefficient, *d*	26E-12 (m/A)
Number of turns in pickup coil, *N*	80
Length of the pickup coil, *l*	30 (mm)
Force (F_0)	0.106 (N)
Relative magnetic permeability, μ_r	300
Moment of Inertia of the beam, I	85E-12

TABLE II
CODED INPUT VARIABLES

Factors	- α	-1	0	1	+ α
r_{ext}	0	0.015	0.05	0.085	0.1
r_{int}	0	0.015	0.05	0.085	0.1

Based on the coefficients presented in Table IV, the harvested power can be modeled by (9):

$$P_{max} = 2.32714 + 3.15177\, r_{int} + 1.09885\, r_{int} \times r_{int} \qquad (9)$$

Therefore, the external damping coefficient has negligible effect on the generated power, and power is sensitive to the internal damping coefficient.

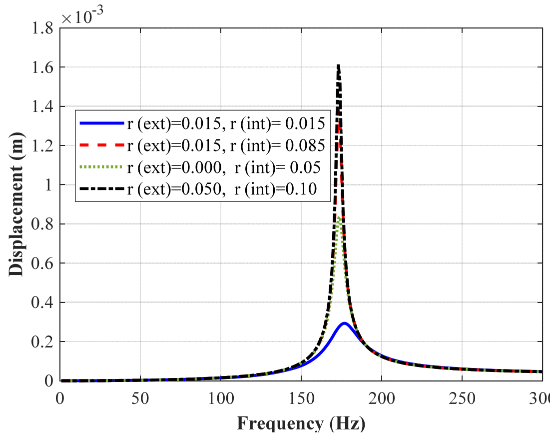

Fig. 2 Frequency response of the harvester under different coefficient

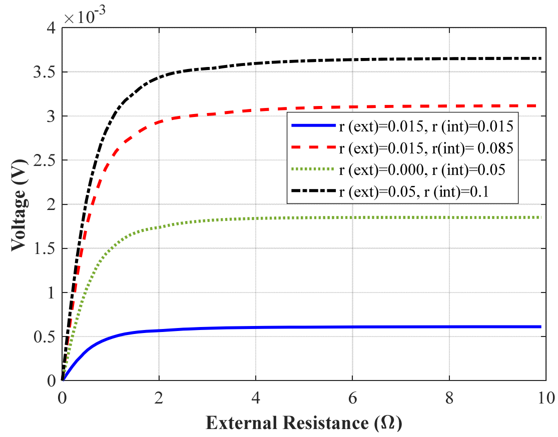

Fig. 3 Highest output voltage of harvester under different damping coefficient

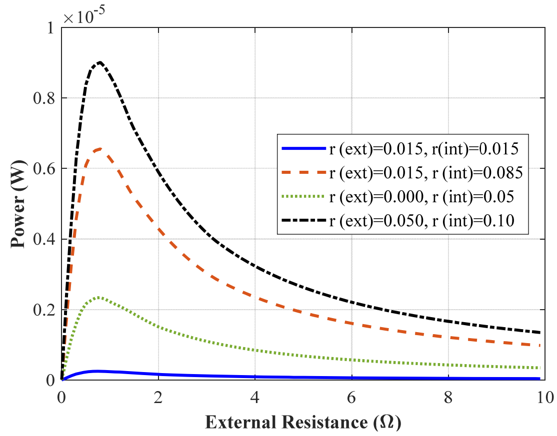

Fig. 4 Highest output power under different damping coefficient

V. Conclusion

A velocity driven energy harvester with a tip excitation was proposed in the paper. The proposed harvester is made of Galfenol material due to its high stiffness, ductility, machinability, and suitability for welding compared to other smart materials. These properties make this smart material a suitable choice for energy harvesting under shocking forces or harsh environments. In this work, the effect of internal and external damping coefficients was investigated. Although, initial investigations show that the values of damping coefficients have a small effect on the resonance frequency of the harvester, the sensitivity analysis made by Response Surface Method (RSM) shows that the harvested power is only sensitive to the internal damping coefficient. Furthermore, it was confirmed that the generated power by the Galfenol is in the micron Watt range.

TABLE III
ANALYTICAL RESULTS USED IN RSM

Order	r_{ext}	r_{int}	P_{max} (μW)
1	0.015	0.015	0.247
2	0.085	0.015	0.247
3	0.015	0.085	6.55
4	0.085	0.085	6.55
5	0.0	0.05	2.33
6	0.1	0.05	2.33
7	0.05	0.0	0.0947
8	0.05	0.1	9.01
9	0.05	0.05	2.337

TABLE IV
COEFFICIENT OF REGRESSION EQUATION AND P_{VALUE} IN INITIAL AND MODIFIED MODELS

Terms	Initial Model		Modified Model	
	Reg. Eq. Coefficient	P_{value}	Reg. Eq. Coefficient	P_{value}
Constant	2.337	0.00	2.3271	0.00
r_{ext}	0.00	1.00	----	----
r_{int}	3.15177	0.00	3.15177	0.00
r_{ext}* r_{ext}	-0.01417	0.145	----	-----
r_{int}* r_{int}	1.097	0.00	1.09885	0.00
r_{int}* r_{ext}	0.00	1.00	-----	-----

REFERENCES

[1] K. Kecik, A. Mitura, S. Lenci, and J. Warminski, "Energy harvesting from a magnetic levitation system," *International Journal of Non-Linear Mechanics,* vol. 94, pp. 200-206, 2017.

[2] M. Ghodsi, "Optimization of Mover Acceleration in DC Tubular Linear Direct-Drive Machine Using Response Surface Method," *International Review of Electrical Engineering (IREE),* vol. 10, p. 492, 2015.

[3] F. A. Samad, M. F. Karim, V. Paulose, and L. C. Ong, "A Curved Electromagnetic Energy Harvesting System for Wearable Electronics," *IEEE Sensors Journal,* vol. 16, pp. 1969-1974, 2016.

[4] W. Shen, S. Zhu, H. Zhu, and Y.-l. Xu, "Electromagnetic energy harvesting from structural vibrations during earthquakes," *Smart Structures and Systems,* vol. 18, pp. 449-470, 2016.

[5] A. Karami, D. Galayko, and P. Basset, "A Novel Characterization Method for Accurate Lumped Parameter Modeling of Electret Electrostatic Vibration Energy Harvesters," *IEEE Electron Device Letters,* vol. 38, pp. 665-668, 2017.

[6] M. Dadkhah, Y. Hojjat, J. Jeon, M. Ghodsi, and M. Modabberifar, "Voltage-induction synchronous electrostatic motor," *The International Journal of Advanced Manufacturing Technology,* vol. 77, pp. 145-164, 2015.

[7] M. Modabberifar, M. Ghodsi, and Y. Hojjat, "Analysis of parameter effects on electrostatic induction dielectric sheet conveyor performance," *International Journal of Precision Engineering Manufacturing,* vol. 13, pp. 65-70, 2012.

[8] M. Ghodsi, N. Hosseinzadeh, A. Ozer, H. R. Dizaj, Y. Hojjat, N. G. Varzeghani*, et al.*, "Development of Gasoline Direct Injector Using Giant Magnetostrictive Materials," *IEEE Transactions on Industry Applications,* vol. 53, pp. 521-529, 2017.

[9] M. Sheykholeslami, Y. Hojjat, M. Ghodsi, M. Zeighami, and K. Kakavand, "Effect of magnetic field on mechanical properties in Permendur," *Materials Science and Engineering: A,* vol. 651, pp. 598-603, 2016.

[10] M. R. Karafi, M. Ghodsi, and Y. Hojjat, "Development of Magnetostrictive Resonant Torsional Vibrator," *IEEE Transactions on Magnetics,* vol. 51, pp. 1-8, 2015.

[11] M. R. Karafi, Y. Hojjat, F. Sassani, and M. Ghodsi, "A novel magnetostrictive torsional resonant transducer," *Sensors and Actuators A: Physical,* vol. 195, pp. 71-78, 2013.

[12] M. Ghodsi, T. Ueno, and T. Higuchi, "Novel Magnetostrictive Bimetal Actuator Using Permendur," *Advanced Materials Research,* vol. 47-50, pp. 262-265, 2008.

[13] M. Ghodsi, T. Ueno, H. Teshima, H. Hirano, T. Higuchi, and E. Summers, "“Zero-power” positioning actuator for cryogenic environments by combining magnetostrictive bimetal and HTS," *Sensors and Actuators A: Physical,* vol. 135, pp. 787-791, 2007.

[14] M. Mohammadzaheri, M. Emadi, M. Ghodsi, E. Jamshidi, I. Bahadur, A. Saleem*, et al.*, "A variable-resistance digital charge estimator for piezoelectric actuators: An alternative to maximise accuracy and curb voltage drop," *Journal of Intelligent Material Systems and Structures,* vol. 30, pp. 1699-1705, 2019.

[15] S. Ghorbanirezaei, Y. Hojjat, and M. Ghodsi, "Design and fabrication of a new piezoelectric paper feeder actuator without mechanical parts," *Smart Structures and Systems,* vol. 24, pp. 183-191, 2019.

[16] M. Ghodsi, S. Mirzamohamadi, S. Talebian, Y. Hojjat, M. Sheikhi, A. Al-Yahmedi*, et al.*, "Analytical, numerical and experimental investigation of a giant magnetostrictive (GM) force sensor," *Sensor Review,* vol. 35, pp. 357-365, 2015.

[17] M. Ghodsi, H. Ziaiefar, K. Alam, M. Mohammadzaheri, A. Al-Yahmedi, and F. K. Omar, "Electromechanical Modelling and Experimental Verification of Cantilevered Permendur Energy Harvester," presented at the IEEE/ASME International Conference on Advanced Intelligent Mechatronics, 2018.

[18] M. Ghodsi, H. Ziaiefar, M. Mohammadzaheri, and A. Al-Yahmedi, "Modeling and Characterization of Permendur Cantilever Beam for Energy Harvesting," *Energy,* vol. 176, pp. 561-569, 2019.

[19] S. Talebian, Y. Hojjat, M. Ghodsi, M. R. Karafi, and S. Mirzamohammadi, "A combined Preisach–Hyperbolic Tangent model for magnetic hysteresis of Terfenol-D," *Journal of Magnetism Magnetic Materials,* vol. 396, pp. 38-47, 2015.

[20] M. Mohammadzaheri and A. J. S. o. A. M. AlQallaf, "Nanopositioning systems with piezoelectric actuators, current state and future perspective," vol. 9, pp. 1071-1080, 2017.

[21] S. Talebian, Y. Hojjat, M. Ghodsi, and M. R. Karafi, "Study on classical and excess eddy currents losses of Terfenol-D," *Journal of Magnetism and Magnetic Materials,* vol. 388, pp. 150-159, 2015.

[22] P. Firoozy, S. E. Khadem, and S. M. Pourkiaee, "Broadband energy harvesting using nonlinear vibrations of a magnetopiezoelastic cantilever beam," *International Journal of Engineering Science,* vol. 111, pp. 113-133, 2017.

[23] H. Jafari, A. Ghodsi, S. Azizi, and M. R. Ghazavi, "Energy harvesting based on magnetostriction, for low frequency excitations," *Energy,* vol. 124, pp. 1-8, 2017.

[24] A. A. Basari, S. Hashimoto, B. Homma, H. Okada, H. Okuno, and S. Kumagai, "Design and optimization of a wideband impact mode piezoelectric power generator," *Ceramics International,* vol. 42, pp. 6962-6968, 2016.

[25] G. Gafforelli, R. Ardito, and A. Corigliano, "Improved one-dimensional model of piezoelectric laminates for energy harvesters including three dimensional effects," *Composite Structures,* vol. 127, pp. 369-381, 2015.

[26] H. Hoshyarmanesh, A. Abbasi, P. Moein, M. Ghodsi, and K. Zareinia, "Design and Implementation of an Accurate, Portable, and Time-Efficient Impedance-Based Transceiver for Structural Health Monitoring," *IEEE/ASME Transactions on Mechatronics,* vol. 22, pp. 2809-2814, 2017.

[27] H. Hoshyarmanesh, M. Ghodsi, and H.-H. Park, "Electrical properties of UV-irradiated thick film piezo-sensors on superalloy IN718 using photochemical metal organic deposition," *Thin Solid Films,* vol. 616, pp. 673-679, 2016.

[28] H. Hoshyarmanesh, N. Nehzat, M. Salehi, and M. Ghodsi, "X-ray diffraction measurement of residual stress in sol-gel grown lead zirconate titanate thick films on nickel-based super alloy substrate,"

Journal of Mechanical Science and Technology, vol. 29, pp. 715-721, 2015.

[29] H. Hoshyarmanesh, N. Nehzat, M. Salehi, M. Ghodsi, H.-S. Lee, and H.-H. Park, "Piezoelectric Transducers on Curved Dispersive Bending Wave and Poke-Charged Touch Screens," *Materials and Manufacturing Processes,* vol. 29, pp. 870-876, 2014.

[30] H. Hoshyarmanesh, M. Ghodsi, M. Kim, H. H. Cho, and H.-H. Park, "Temperature Effects on Electromechanical Response of Deposited Piezoelectric Sensors Used in Structural Health Monitoring of Aerospace Structures," *Sensors,* vol. 19, p. 2805, 2019.

[31] M. Sheykholeslami, Y. Hojjat, M. Ghodsi, K. Kakavand, and S. Cinquemani, "Investigation of ΔE Effect on Vibrational Behavior of Giant Magnetostrictive Transducers," *Shock and Vibration,* vol. 2015, pp. 1-9, 2015.

[32] M. R. Sheykholeslami, Y. Hojjat, S. Cinquemani, M. Ghodsi, and M. Karafi, "An approach to design and fabrication of resonant giant magnetostrictive transducer," *Smart Structures and Systems,* vol. 17, pp. 313-325, 2016.

[33] M. Ghodsi and M. Modabberifar, "Quality factor, static and dynamic responses of miniature galfenol actuator at wide range of temperature," *International Journal of Physical Sciences,* vol. 6, pp. 8143-8150, 2011.

[34] A. Erturk and D. J. Inman, "A distributed parameter electromechanical model for cantilevered piezoelectric energy harvesters," *Journal of vibration and acoustics,* vol. 130, p. 041002, 2008.

[35] N. E. Dutoit, B. L. Wardle, and S.-G. Kim, "Design considerations for MEMS-scale piezoelectric mechanical vibration energy harvesters," *Integrated ferroelectrics,* vol. 71, pp. 121-160, 2005.

[36] M. Ghodsi, M. Mohammadzaheri, H. Ziaiefar, A. Al-Yahmedi, and F. K. Omar, "Effect of Magnetostrictive Properties on the Performance of Velocity-Driven Harvester," in *2019 20th International Conference on Research and Education in Mechatronics (REM)*, 2019, pp. 1-6.

[37] M. Ghodsi, H. Ziaiefar, M. Mohammadzaheri, and A. Al-Yahmedi, "Development of Magnetostrictive Harvester for Unmanned Aerial Vehicles (UAV)," in *2019 1st International Conference on Unmanned Vehicle Systems-Oman (UVS)*, 2019, pp. 1-6.

[38] G. Engdahl and I. Mayergoyz, *Handbook of Giant Magnetostrictive Materials* New York: Academic Press 2000.