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COMSOL MODEL Notes

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Abstract
In recent decades, the fast growth of infrastructure, industrial applications, medical applications, and the energy-saving importance make converting wasted surrounding vibrations to useful electrical power by employing piezoelectric cantilevers a promising technique. Piezoelectric energy harvesting replaces the battery employed to operate low-power- sensors. Also, this power can operate wireless sensor networks (WSN) in buildings, power plants, the manufacturing services (machines). Also, can be employed for structural health monitoring applications. Besides, the motion of blood and air can be harvested using piezoelectric to replace the battery in some medical applications. The harvested power can run sensors, radio frequency (RF) transmitters, and microprocessors. So, piezoelectric energy harvesting is a growing technique that can be employed in our country in many applications. In this research, we aim to harvest the wasted energy of the buildings, transportation, and manufacturing services. A harvester consisting of two composite piezoelectric beams is proposed. The modeling and simulation are conducted using the Finite Element Method (FEM) COMSOL. The output voltage and power are simulated over a wide frequency range (10-30 Hz) (targeted applications frequency range). Also, the mode shapes of the proposed harvester are presented. The effect of the base excitation acceleration is investigated. Besides the stress distribution over the harvester is investigated to avoid the failure. The efficiency and durability of the harvester are checked.

Keywords: *Piezoelectric material, two modes, FEM, energy harvesting.*

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I. Introduction

Converting the wasted energy into useful electrical energy to replace the battery in many applications [1–4]. This harvested energy operates wireless sensor networks (WSN) which are mainly utilized in structural health monitoring to protect and monitor many

structures in many industrial applications [5, 6] and to run sensors [7, 8]. The harvested energy can operate a radio frequency (RF) transmitter [9], and microprocessor [10, 11]. There are surrounding available energy sources like structural vibrations of bridges, transportation, rotating machines, and liquid and wind flow energy [12]. Simple structure, reliability, availability, high efficiency, and low cost let piezoelectric energy harvesting attract importance and attention in the last period [13, 14].

Zhang and Qin [15] presented a device for frequency up-conversion harvesters [15]. Fu and Yeatman [16] presented a harvester for broadband and low rotational speed harvester. Nonlinear harvesters based on an external magnet were presented [17–19]. This approach has a drawback to the large dimensions relative to the introduced broadband enhancement. Another approach is resonance tuning using the active method. The low net output power technique (active piezoelectric harvester) which utilizes a controller and sensor has been investigated [20].

Utilizing an array of piezoelectric energy harvesters with different natural frequencies has been introduced in many broadband natural frequency applications [21–28]. Maximizing and improving the output power of the harvesters were investigated and studied by [29-31]. Silveira et al. [32] proposed a harvester to harvest the vibration energy of a tilting pad bearing. Liu et al. [33] proposed a tri-stable harvester to harvest the power in many directions.

In this study, FEM COMSOL is employed to evaluate the natural frequencies of the first and second modes of vibrations. Also, the electrical resistance dependence study is conducted using FEM to determine the optimal resistance which gives the maximum output power. Then, the output power and voltage frequency dependence study are implemented. The efficiency of the proposed design is tested. This paper aims to harvest the ambient vibrations with a frequency lower than 100 Hz and acceleration lower than 15 m/s2 [34-37]. The wasted energies are excited in buildings, bridges, cars, and structures. To harvest this wasted power, two piezoelectric cantilevers are employed, then the harvested power operates a sensors network in many industrial and medical applications (see Fig. 1).

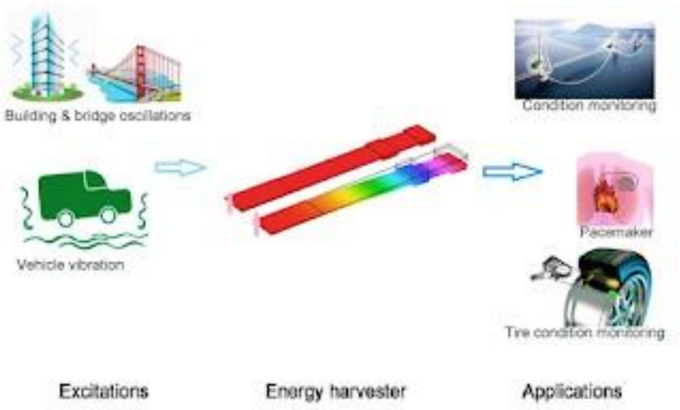


Fig.1. proposed harvester harvests the wasted vibration(energy) to an electrical power utilized in many industrial and medical applications.

II. Modeling and simulation

2.2. Analytical Modeling

In this section, the modelling of two cantilevers of piezoelectric beams using FEM (COMSOL 6) is presented. Lefeuvre et al. [38] derived an analytical model of a piezoelectric energy harvester in terms of base excitation U(m), c_p capacitance (C/V), V_{re}voltage (V), mass (Kg), α_2 electromechanical coupling coefficient, and C_V damping coefficient (N/ms). The output power can be represented as :

(1)

After the reduction:

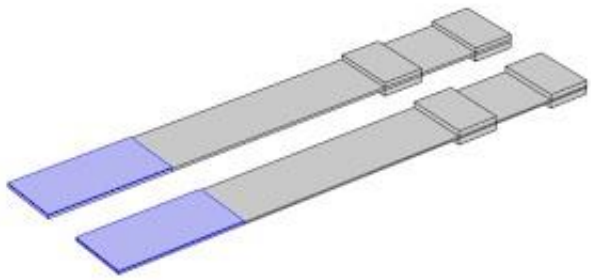
$$Power = V_{re}\left(\frac{2\alpha_2}{\frac{\pi}{2}+Rc_p\omega_n}+C_v\frac{\frac{\pi}{2}+Rc_p\omega_n}{\alpha_2 R}\right)$$

(2)

Where, ω_n is the natural frequency (Hz), and R is the electrical resistance (Ω).

2.2. FEM COMSOL Modeling and Natural Frequency Evaluation

Fig.2 reveals the proposed model employed in this study. The model consists of two cantilevers that are covered with piezoelectric layers of 30 mm at the fixed end. Also, four masses are employed as two tip masses and two enhanced masses. The masses are employed to control the frequency where the frequency mainly depends on the stiffness and mass. The base material is selected to be a steel layer for its stiffness, strength, and elasticity. The steel layers are coated with a piezoelectric layer of PZT-5H at the fixed end. Table 1 lists the properties of the material employed to construct the harvest in terms of density, elasticity, and Poisson ratio. Table 2 lists and summarizes the geometric dimensions utilized in this study. Fig.2. reveals the mesh quality of the proposed harvester. Fig. 3 the value of natural frequencies of the first two modes. Also, the mode shapes are demonstrated.



Steel Layer

Piezoelectric

Beam 1

Beam 2

second masses

Figure 1: The array model used in FEA COMSOL modelling.

Table 1. The properties of the base and piezoelectric materials.

Material	Steel	Piezoelectric (PZT-5H)
Density (kg m-3)	8000	7500
Young's modulus (GPa)	193	64
Poisson's ratio	0.29	0.3
Coupling coef.(CV / Nm)	-	0.12
Strain constant (m/V×10-12)	-	274

Table 2. Geometric parameters of piezoelectric array harvester.

Parameters	Steel cantilevers	Piezoelectric (PZT-5H)
Length (mm)	120/cantilever	30
Width (mm)	15/cantilever	15
Thickness (mm)	0.5 and 0.7	0.3

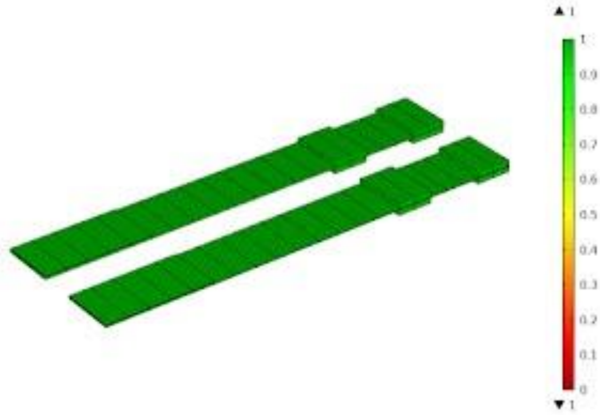
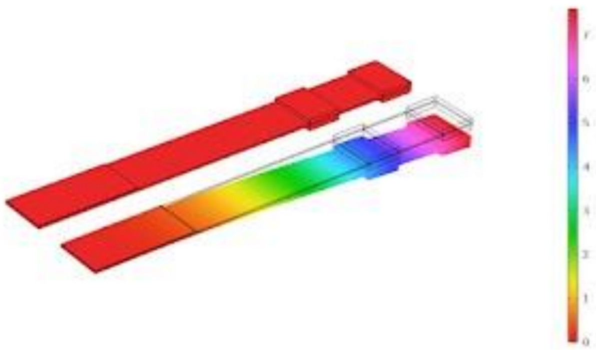
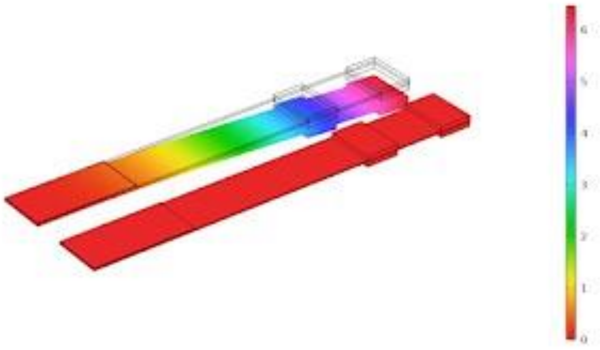


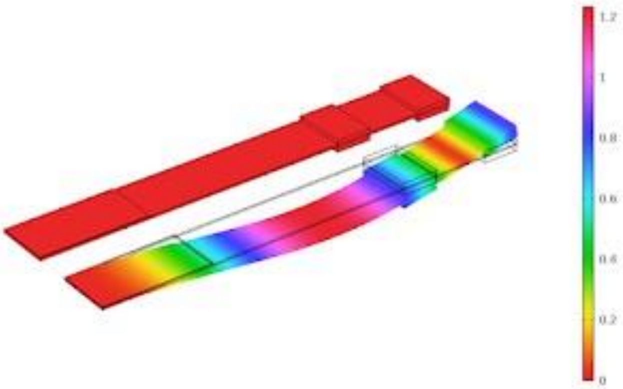
Fig.2. The mesh quality of the proposed harvester.



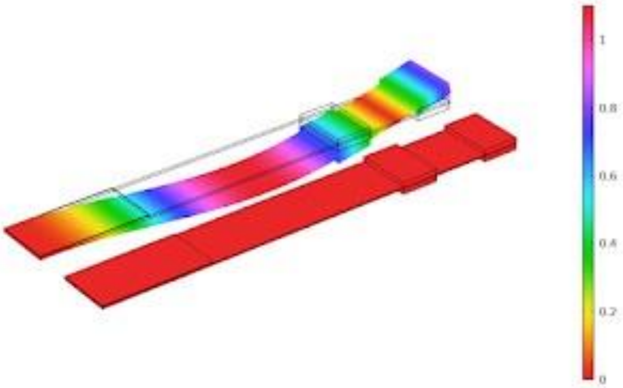
(a)



(b)



(c)



(d)

Fig. 3. The mode shapes and the resonant frequencies of the array harvester (a) mode 1 of beam 1 (14.3 Hz), (b) mode 1 of beam 2(22 Hz), (c) mode 2 of beam 1 (129.7 Hz), (d) mode 2 of beam 2 (193.19 Hz).

III. Results and discussions

The simulations of the proposed model are conducted based on 15 m/s2 as base excitation acceleration. The proposed acceleration is the maximum acceleration in the applications of bridges and transportation. Also, the simulations are conducted at a frequency lower than 100 Hz. The simulations are conducted in forced and damped vibration modes where the damping coefficient is selected to be 0.05. Figs. 4-7 show the electrical resistance effect on the output power and voltage. Figs. 4-5 reveal the simulations of the output voltage and power respectively over a range from the resistance at the first mode natural frequency. It is observed from Figs. that the optimal resistance that produces the maximum electrical power is 100 KΩ. Figs. 6-7 reveal the simulations of the output voltage and power respectively over a range from the resistance at the second mode natural frequency. It is observed from Figs. that the optimal resistance that produces the maximum electrical power is 100 KΩ. so the frequency domain study is conducted at 100 KΩ as electrical resistance. Figs. 8-9 show the frequency response of the output voltage and output power. It is observed that the maximum voltage is around 100 V and the maximum power is around 50 mW. The resulting power and voltage are high enough to operate a sensor in industrial applications. Also, the effect of increasing the acceleration base excitation is investigated as shown in Fig. 10, so we can determine the output power and voltage at any input (acceleration). Fig. 11 shows the stress distribution over the harvester at the 1.5 g base excitation. It is proven the reliability of the harvester where the maximum stress is lower than the strength of the steel and piezoelectric materials. Fig. 12 reveals the deflection distribution over the two beams around the first two natural frequencies at 14 and 22 Hz. Fig. 13 shows the strain distribution over the two beams around the first two natural frequencies at 14 and 22 Hz. Fig. 14 reveals the potential voltage distribution over the piezoelectric material around the first two natural frequencies at 14 and 22 Hz.

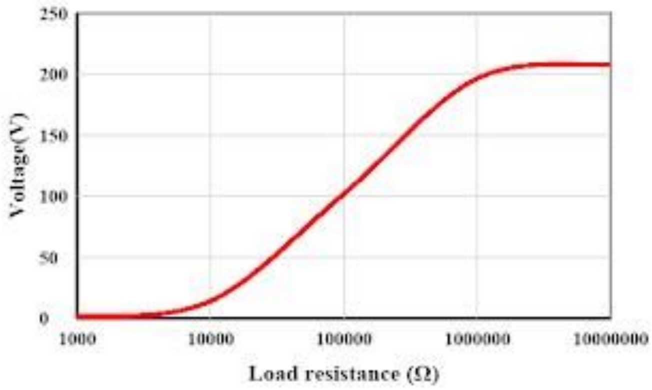


Fig. 4. The load resistance study of the voltage at the first mode.

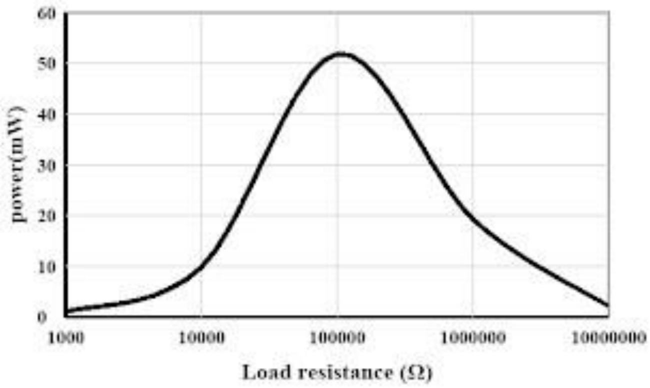


Fig. 5. The load resistance study of the power at the first mode.

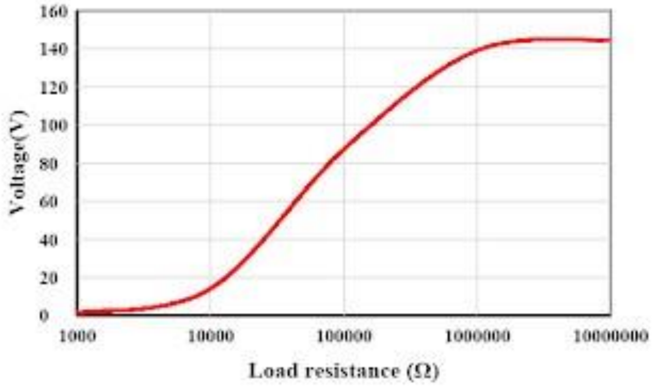


Fig. 6. The load resistance study of the voltage at the second mode.

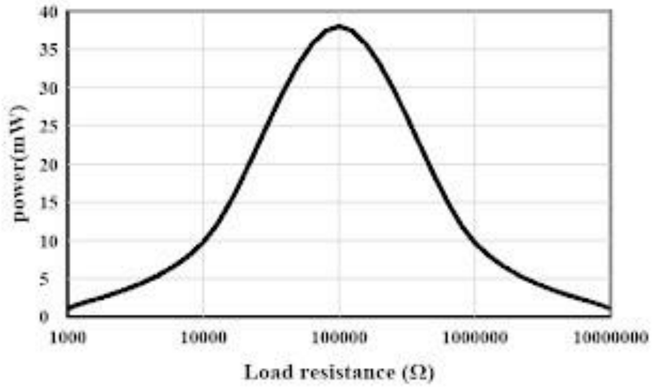
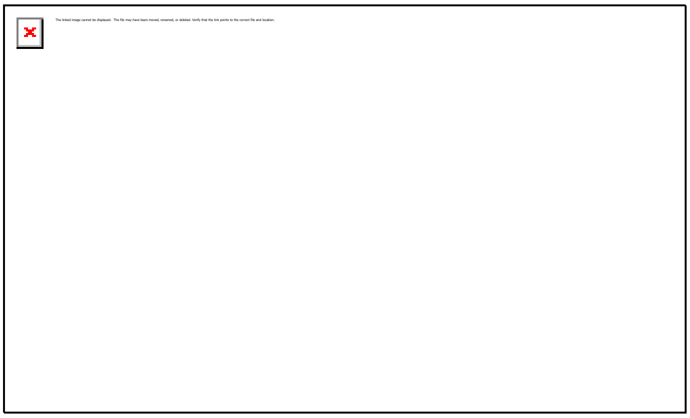
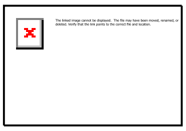


Fig. 7. The load resistance study of the power at the second mode.





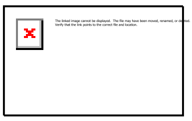


Fig. 8. The frequency response study of the voltage.

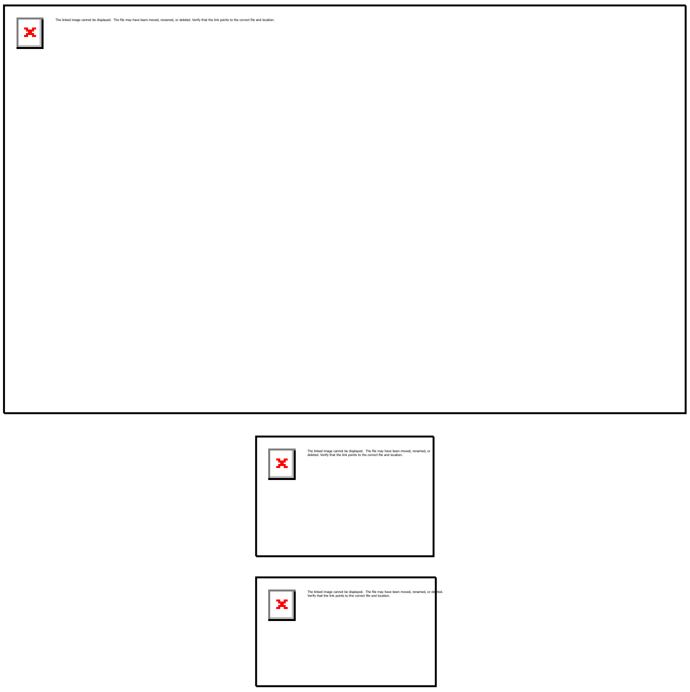


Fig. 9. The frequency response study of the power.

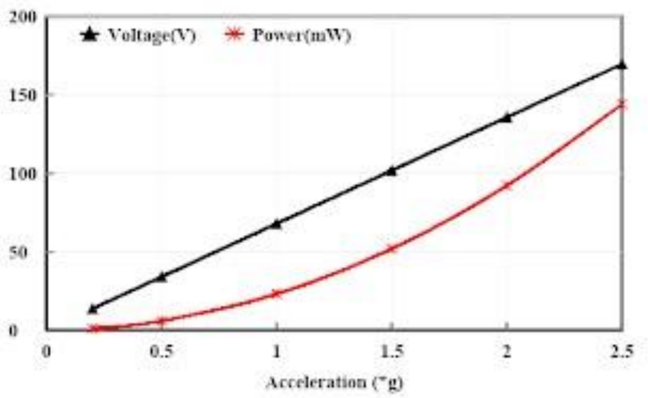


Fig. 10. Output power and voltage against the base excitation acceleration.

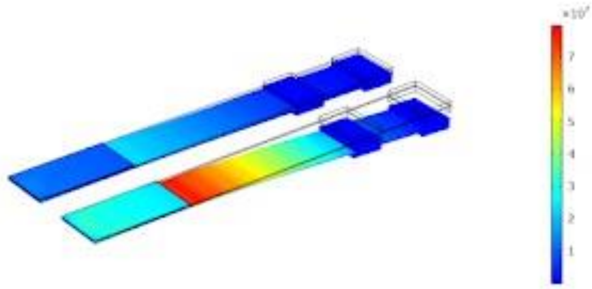
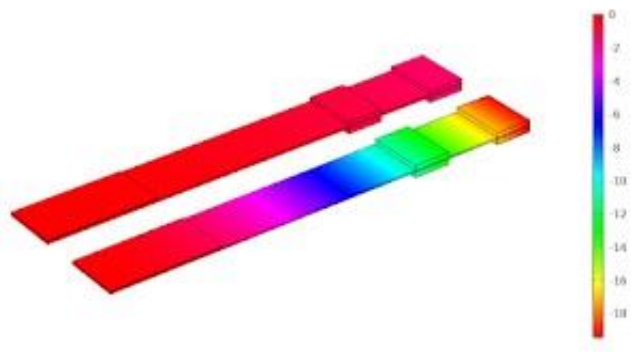
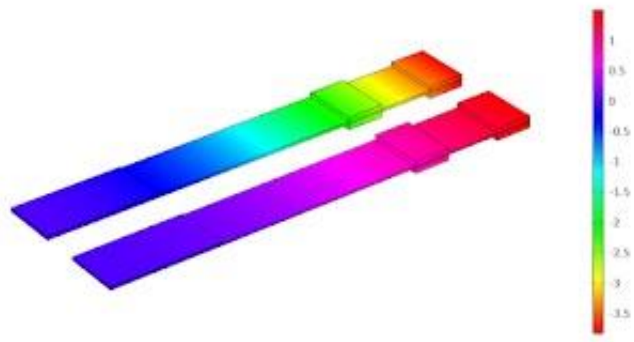


Fig. 11. Stress distribution over the two beams at 1.6 g acceleration.



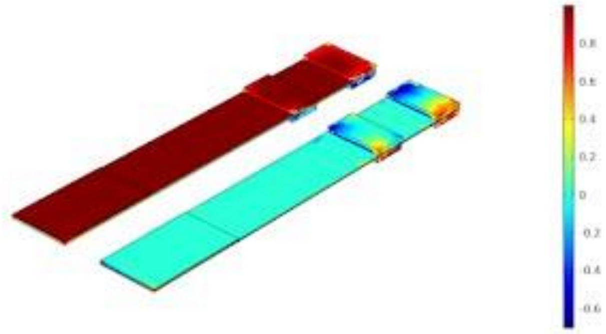
(a)



(b)

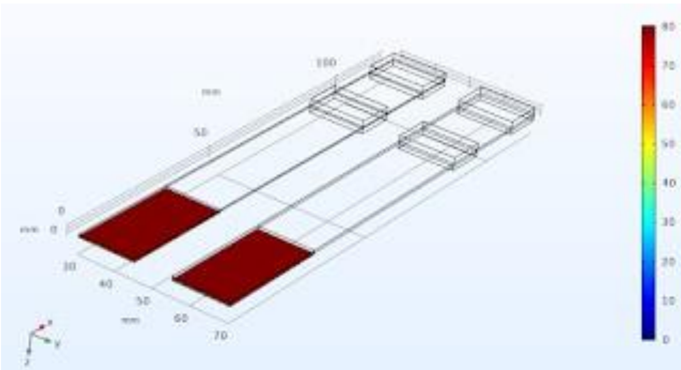
Fig. 12. The deflection (displacement (mm)) in Z direction distribution over the two beams (a) at 14 Hz, (b) at 22 Hz.

(a)

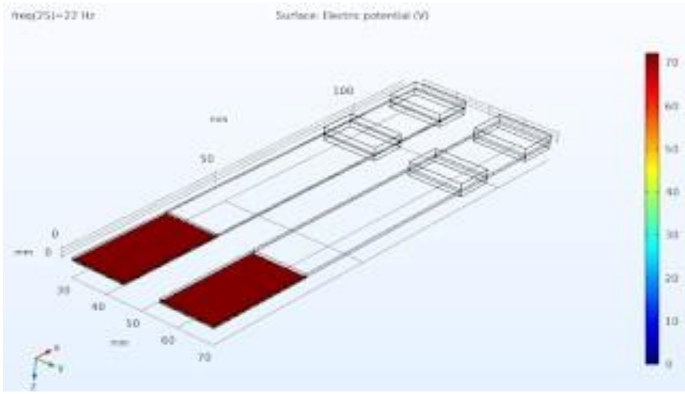


(b)

Fig. 13. The strain in X direction distribution over the two beams (a) at 14 Hz, (b) at 22 Hz.



(a)



(b)

Fig. 14. The potential voltage(V) distribution over the two beams (a) at 14 Hz, (b) at 22 Hz.

IV. Conclusions

A harvester consisting of two composite piezoelectric beams was constructed to harvest the wasted energy of surroundings. The modeling and simulation were conducted using the Finite Element Method (FEM) COMSOL. The resistance dependence study was conducted at the first and second mode shapes. It was found that the optimal resistance is 100 KΩ. The output voltage and power were simulated over a wide frequency range. It is observed that the maximum power is around 50 mW and the maximum voltage is around 100 V which can operate a sensor in industrial applications during structural health monitoring. Also, the mode shape of the vibrations was presented. The effect of the base excitation acceleration was investigated. Finally, the stress distribution over the harvester was introduced. The efficiency and durability of the harvester were investigated. The deflection, strain, and potential voltage distribution along the two beams were presented around the first two natural frequencies.

References

[1]. I. Izadgoshasb, Y.Y. Lim, N. Lake, L.H. Tang, R.V. Padilla, T. Kashiwao, Optimizing orientation of piezoelectric cantilever beam for harvesting energy from human walking, Energ. Convers. Manage. 161 (2018) 66–73.

[2]. A.M. Stamatellou, A.I. Kalfas, Experimental investigation of energy harvesting from swirling flows using a piezoelectric film transducer, Energ. Convers. Manage. 171 (2018) 1405–1415.

[3]. S. Kim, M.M. Tentzeris, A. Georgiadis. Hybrid printed energy harvesting technology for self-sustainable autonomous sensor application, Sensors-Basel 19 (2019).

[4]. U. Alvarado, A. Juanicorena, I. Adin, B. Sedano, I. Gutierrez, No J. Energy harvesting technologies for low-power electronics.

[5]. Trans Emerg Telecommun T. 23 (2012) 728–741.

[6]. G. Martinez, S.F. Li, C. Zhou, Wastage-aware routing in energyharvesting wireless sensor networks, IEEE Sens. J. 14 (2014) 2967–2974.

[7]. F. U Khan, I. Ahmad, Review of energy harvesters utilizing bridge vibrations. Shock Vib, 2016. https://doi.org/10.1155/2016/1340402.

[8]. S. Jeong, Z. Foo, Y. Lee, J.Y. Sim, D. Blaauw, D. Sylvester, A fullyintegrated 71 nW CMOS temperature sensor for low power wireless sensor nodes, IEEE J. Solid State Circ. 49 (2014) 1682– 1693.

[9]. G. Chen, H. Ghaed, R. Haque, M. Wieckowski, Y. Kim, G. Kim, D. Fick, D. Kim, M. Seok, K. Wise, A cubic-millimeter energyautonomous wireless intraocular pressure monitor, in: IEEE International Solid-State Circuits Conference, IEEE, 2011, pp. 310–312.

[10]. H. Okada, T. Itoh, T. Masuda, Development of custom CMOS LSI for ultra-low power wireless sensor node in health monitoring systems, in: SENSORS, IEEE, 2011, pp. 1197–1200.

[11]. S. Hanson, M. Seok, Y.-S. Lin, Z. Foo, D. Kim, Y. Lee, N. Liu, D. Sylvester, D. Blaauw, A low-voltage processor for sensing applications with picowatt standby mode, IEEE J. Solid State Circ. 44 (2009) 1145–1155.

[12]. Y. Kuo, P. Pannuto, G. Kim, Z. Foo, I. Lee, B. Kempke, P. Dutta, D. Blaauw, Y. Lee, MBus: a 17.5 pJ/bit/chip portable interconnect bus for millimeter-scale sensor systems with 8 nW standby power, in: Proceedings of the IEEE 2014 Custom Integrated Circuits Conference, IEEE, 2014, pp. 1–4.

[13]. M. Safaei, H. A Sodano, S. Anton, A review of energy harvesting using piezoelectric materials: state-of-the-art a decade later

[14]. (2008–2018), Smart Mater. Struct. 28 (2019) 113001.

[15]. K. Moon, J. Choe, H. Kim, D. Ahn, J. Jeong, A method of broadening the bandwidth by tuning the proof mass in a piezoelectric energy harvesting cantilever, Sensor Actuat. aPhys 276 (2018) 17–25.

[16]. X.Y. Li, D. Upadrashta, K.P. Yu, Y.W. Yang, Sandwich piezoelectric energy harvester: analytical modeling and experimental validation, Energ. Convers. Manage. 176 (2018) 69–85.

[17]. J.H. Zhang, L.F. Qin, A tunable frequency up-conversion wideband piezoelectric vibration energy harvester for lowfrequency variable environment using a novel impact- and ropedriven hybrid mechanism, Appl. Energ. 240 (2019) 26–34.

[18]. H.L. Fu, E.M. Yeatman, A methodology for low-speed broadband rotational energy harvesting using piezoelectric transduction and frequency up-conversion, Energy 125 (2017) 152–161.

[19]. F. Cottone, H. Vocca, L. Gammaitoni, Nonlinear energy harvesting, Phys. Rev. Lett. 102 (2009) 080601 https://doi.org/10.1103/PhysRevLett.102.080601.

[20]. A.F. Arrieta, P. Hagedorn, A. Erturk, D.J. Inman, A piezoelectric bistable plate for nonlinear broadband energy harvesting, Appl. Phys. Lett. 97 (2010) 104102https://doi.org/10.1063/1.3487780.

[21]. S.C. Stanton, C.C. McGehee, B.P. Mann, Nonlinear dynamics for broadband energy harvesting: Investigation of a bistable piezoelectric inertial generator, Phys. Nonlinear Phenom. 239 (2010) 640–653, https://doi.org/10.1016/j.physd.2010.01.019.

[22]. C. Peters, D. Maurath, W. Schock, F. Mezger, Y. Manoli, A closed-loop wide-range tunable mechanical resonator for energy harvesting systems, J. Micromech. Microeng. 19 (2009) 094004, https://doi.org/10.1088/0960-1317/19/9/094004.

[23]. T. Yildirim, J. Zhang, S. Sun, G. Alici, S. Zhang, W. Li, Design of an enhanced wideband energy harvester using a parametrically excited array, Journal of Sound and Vibration 410 (2017) 416428.

[24]. H.-C. Song, P. Kumar, R. Sriramdas, H. Lee, N. Sharpes, M.-G. Kang, D. Maurya, M. Sanghadasa, H.-W. Kang, J. Ryu, W.T. Reynolds, S. Priya, Broadband dual phase energy harvester: vibration and magnetic field, Appl. Energy 225 (2018) 1132– 1142, https://doi.org/10.1016/j.apenergy.2018.04.054.

[25]. M. Ferrari, V. Ferrari, M. Guizzetti, D. Marioli, A. Taroni, Piezoelectric multifrequency energy converter for power harvesting in autonomous microsystems, Sensor Actuator A Phys. 142 (2008) 329–335, https://doi.org/10.1016/j.sna.2007.07.004.

[26]. I.C. Lien, Y.C. Shu, Array of piezoelectric energy harvesting by the equivalent impedance approach, Smart Mater. Struct. 21 (2012) 082001 (8pp).

[27]. I.C. Lien, Y.C. Shu, Array of piezoelectric energy harvesters, Proc. SPIE 7977, Active and Passive Smart Structures and Integrated Systems 2011, 79770K (2011) https://doi.org/10.1117/12.880260.

[28]. H.C. Lin, P.H. Wu, I.C. Lien, Y.C. Shu, Analysis of an array of piezoelectric energy harvesters connected in series, Smart Mater. Struct. 22 (2013) 094026 (11pp).

[29]. L. Jianga, Y. Yang, R. Chen, G. Lu, R. Li, D. Li , M.S. Humayun, K.K. Shung, J. Zhu, Y. Chen, Q. Zhou, Flexible piezoelectric ultrasonic energy harvester array for bio-implantable wireless generator, Nano Energy, 56 (2019) 216-224.

[30]. H. Deng, Y. Du, Z. Wang, J. Ye, J. Zhang, M. Ma, X. Zhong, Polystable energy harvesting based on synergetic multistable vibration, Communications Physics-Nature (2019) 2-21.

[31]. C. Lu, C. Tsui, W. Ki, Vibration energy scavenging system with maximum power tracking for micropower applications, IEEE Transactions on Very Large Scale Integration (VLSI) Systems 19 (11) (2011) 2109-2119.

[32]. Y. Shin, J. Choi, S. J. Kim, S. Kim, D. Maurya, T. Sung, S. Priya , C. Kang, H. Song, Automatic resonance tuning mechanism for ultra-wide bandwidth mechanical energy harvesting, Nano Energy 77 (2020) 1-11.

[33]. X. Wang, Y. Xia, G. Shi, H. Xia, M. Chen, Z. Chen, Y. Ye, L. Qian, A Novel MPPT Technique Based on the Envelope Extraction

[34]. Implemented With Passive Components for Piezoelectric Energy Harvesting, IEEE Transactions on Power Electronics 36 (11) (2021) 12685-12693.

[35]. A. Silveira, G. Danie, Optimization analysis of an energy harvester for smart tilting pad journal bearings considering higher vibration modes, Mechanical Systems and Signal Processing 166 (2022) 108404.

[36]. C. Liu, B. Liao, R. Zhao, K. Yu, H. Lee, J. Zhao, stroke tri-stable vibration energy harvester: Modelling and experimental validation, Mechanical Systems and Signal Processing, 168(2022) 108699.

[37]. Harvesting traffic-induced vibrations for structural health monitoring of bridges T V Galchev1 , J McCullagh1 , R L Peterson1 and K Najafi1 Published 29 September 2011 • 2011

[38]. IOP Publishing Ltd Journal of Micromechanics and Microengineering, Volume 21, Number 10 Citation T V Galchev et al 2011 J.

[39]. M. Karimi, A.H. Karimi, R. Tikani, S. Ziaei-Rad, Experimentaland theoretical investigations on piezoelectric-based energy harvesting frombridge vibrations under travelling vehicles, Int. J. Mech. Sci. 119 (2016).

[40]. Piezoelectric energy harvesting from tra_c-induced bridge vibrations Michael Peigney1, Dominique Siegert2 https://halenpc.archives-ouvertes.fr/hal-00859131 Submitted on 11 Sep 2013.

[41]. "Nonlinear energy harvesting from base excitation in automotive applications" Presented at the 3rd Biennial International

[42]. Conference on Powertrain Modelling and Control (PMC 2016), Loughborough University,7-9th Sept, 2016 https://aka.ms/officeandroidshareinstall.

[43]. D.A.E. Lefeuvre, C. Richard, D. Guyomar, Buck-Boost Converter for Sensor less Power Optimization of Piezoelectric Energy

[44]. Harvester, Transactions on Power Electronics 5 (2007) 20-34.