JETIR.ORG ISSN: 2349-5162 | ESTD Year : 2014 | Monthly Issue
JOURNAL OF EMERGING TECHNOLOGIES AND INNOVATIVE RESEARCH (JETIR)
An International Scholarly Open Access, Peer-reviewed, Refereed Journal

Identification of System Model for a Piezoelectric Energy Harvesting Device

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Abstract: The piezoelectric effect describes the property of some crystalline materials to polarize when subjected to a mechanical deformation thereby generating a potential difference, and at the same time to deform in an elastic manner when traversed by electrical current Discovered in 1880 by French physicists Jacques and Pierre Curie, the piezoelectric effect is defined as the linear electromechanical interaction between the mechanical and electrical state such that electric charge is accumulated in response to the applied mechanical stress. Piezoelectric crystals use piezoelectric effect to convert mechanical strain into electric current or voltage that is used to power up low power devices. It is an efficient way of energy harvesting and aims at providing clean energy solutions to everyday needs. In this paper COMSOL Multiphysics 5.6 has been used to develop the system model of a cantilever shaped piezoelectric energy harvesting device. The mathematical model developed can be later utilized to study the various responses of the device.

Index Terms **- Energy harvesting, piezoelectric, self-powered device, system identification.**

I. INTRODUCTION

Energy harvesting is a clean and efficient technology which involves conversion and collection of energy from the surroundings to power up small electronic devices which typically consume power in the range of micro watts to few watts [1]. The global market of devices powered by ambient energy is predicted to a total of 2.6 billion units by 2024 [2]. In this regard the technology of energy harvesting has grown into several fields of applications including automatic home appliances, medical appliances, individual wearable electronic goods, military equipment etc. In the present scenario these appliances depend on power derived from the battery and thereby need a medium for storage. However, these batteries need to be periodically recharged, replaced and also is limited by its capacity. Hence, continuous monitoring is required and because of the environmental concerns related to its disposal battery is losing its importance in powering up equipment of daily use. We have to thereby harvest energy from the environment into electricity so that we can increase the lifetime of the devices and form a self-powered system by getting rid of the batteries [3-18]. Piezoelectric crystals prove to be an efficient way of energy harvesting which uses the piezoelectric effect to convert mechanical strain into electric current or voltage which can be used to power up devices working on low power. In the late 1990s piezoelectric energy harvesting had started [19][20] and it remains an emerging technology with a wide range of applications. Piezo harvester-based battery-less wireless doorbell push button and classical wireless wall switch was talked about in 2016. Piezoelectric systems can be used to harness motion from leg and arm motion, shoe impacts, and blood pressure and convert it into electrical power. To power up implantable or wearable sensors. As the vibration of motion from humans comes in three directions, a single piezoelectric cantilever based omni-directional energy harvester is created by using 1:2 internal resonance [21]. Piezo elements are used in walkways [22][23] to recover the "people energy" of footsteps and can also be embedded in shoes to recover "walking energy". Here piezoelectric cantilevers are adopted to harvest energy from the above systems. However, the major drawback in this system is a gradient strain distribution, where the piezoelectric transducer is not fully utilized. In order to do away with it triangle shaped and L-shaped cantilever are proposed for uniform strain distribution [24][25][26].

In this work the system model of a cantilever shaped piezoelectric energy harvesting device is identified using the MATLAB system identification toolbox. System identification is a methodology to build up the mathematical model of any unknown dynamic system by measurement of the input and output signals of the system. It uses various statistical methods to identify the mathematical model of a given dynamic system from the measured input and output data [27][28].

II. THEORETICAL BACKGROUND OF THE STUDY

Piezoelectric Effect is a reversible process in which certain materials are able to generate stress when an electric field is applied or can generate electricity when stress is applied. When piezoelectric material is placed under mechanical stress, a shifting of the positive and negative charge centers in the material takes place. This distortion causes a reorientation of electric charges within the material, resulting in a relative displacement of positive and negative charges which then results in an external electrical field. Again when reversed, an outer electrical field either stretches or compresses the piezoelectric material. The charge displacement induces surface charges on the material of opposite polarity between the two sides. The electrodes are then implanted on the surface of the material to obtain a voltage at the output. The induced voltage for a rectangular block of material is given by:

$$V = \frac{sFD}{a}$$

Where, F is the applied force, D is the thickness of the material, s being the piezoelectric constant and a being the area of material. Various materials exhibiting piezoelectric behavior include quartz, synthetic ones such as lithium sulphate and ferroelectric ceramics such as barium titanate.

Piezoelectric crystals are electrically neutral when they are not subjected to any mechanical stress. Electrical charges of piezoelectric crystals are perfectly balanced even if the atoms inside them are not symmetrically arranged. This is because of cancellation of a positive charge in one place by a negative charge nearby. However, if a tensile or compressive force is applied to the piezoelectric crystal, the atomic structure gets deformed. This causes some of the atoms to come closer and some of the atoms to go further apart leading to upset the balance of positive and negative charges, and causing net electrical charges to appear. This effect carries through the whole structure so net positive and negative charges appear on opposite, outer faces of the crystal.

The direct piezoelectric effect in a piezoelectric crystal is explained below. Materials that do not have a center of symmetry can work as a piezoelectric material. For example quartz crystal rochelle salt, lead zirconate titanate (PZT), barium titanate etc are piezoelectric materials. When no mechanical stress is applied to the crystal the center of mass of the positive and negative atoms coincide at the same point, hence no charge is created on the opposite surface of the crystal. When a tensile stress is applied to the crystal as shown in Fig. 1, the center of mass of both positive and negative ions shift, hence a net polarization is created in the crystal surface. When a compressive stress is applied to the crystal as shown in Fig. 1, opposite polarization is created on the crystal surface.

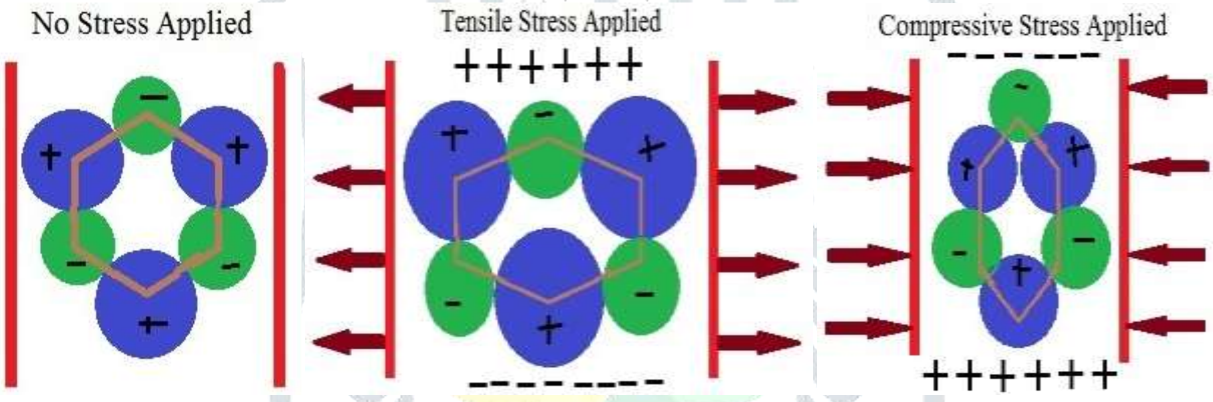

Figure 1: Effect of piezoelectricity in crystals

The piezoelectric mechanical system can be modeled by a simple R-L-C (resistor-inductor-capacitor) series circuit with the help of mechanical-electrical analogy for further study and analysis purposes. A voltage source along with a parallel capacitance can be added to the circuit at the beginning to represent the electrode and thereby completely representing a piezoelectric material based energy harvesting system.

III. EXPERIMENTAL PROBLEM STATEMENT

In this experiment we are modeling the direct effect of piezoelectricity in a simple case. In Fig. 2, a cantilever of piezoelectric layer is shown which is clamped at one side and a harmonic force is applied to the other side. The force is a sine function with an amplitude of 1N and a frequency of 4Hz. The top and bottom surfaces of the piezoelectric layer are covered by electrodes. The length, breadth and width of the piezoelectric layer is shown in Fig. 2. The cantilever produces electric potential across its two electrodes under the application of mechanical agitation. The piezoelectric cantilever can be used as an energy harvesting device. In this experiment the mathematical model of the piezoelectric cantilever working as an energy harvesting device is identified using the measurements of the applied stress and the generated electric potential through simulation.

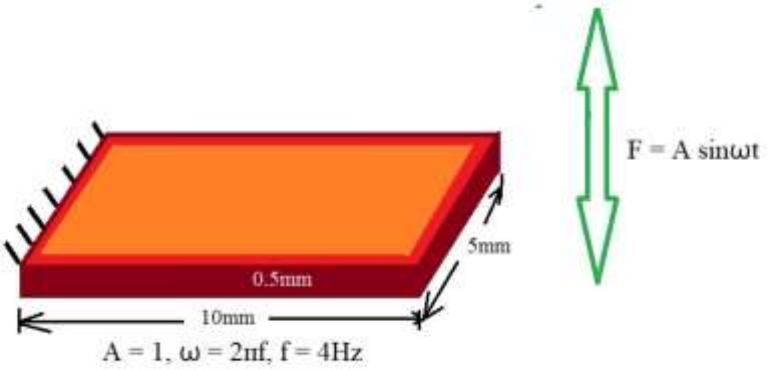

Figure 2: Block diagram of the piezoelectric cantilever working as an energy harvesting device

IV. METHODOLOGY

The piezoelectric cantilever is simulated using COMSOL Multiphysics 5.6 software. The graphical user interface (GUI) of the COMSOL multiphysics 5.6 software is used to simulate the cantilever. The cantilever with its dimension is shown in Fig. 3. Lead Zirconate Titanate (PZT) is used as piezoelectric material. The graphical user interface (GUI) of the COMSOL multiphysics 5.6 software in which the cantilever is simulated is shown in Fig. 3.

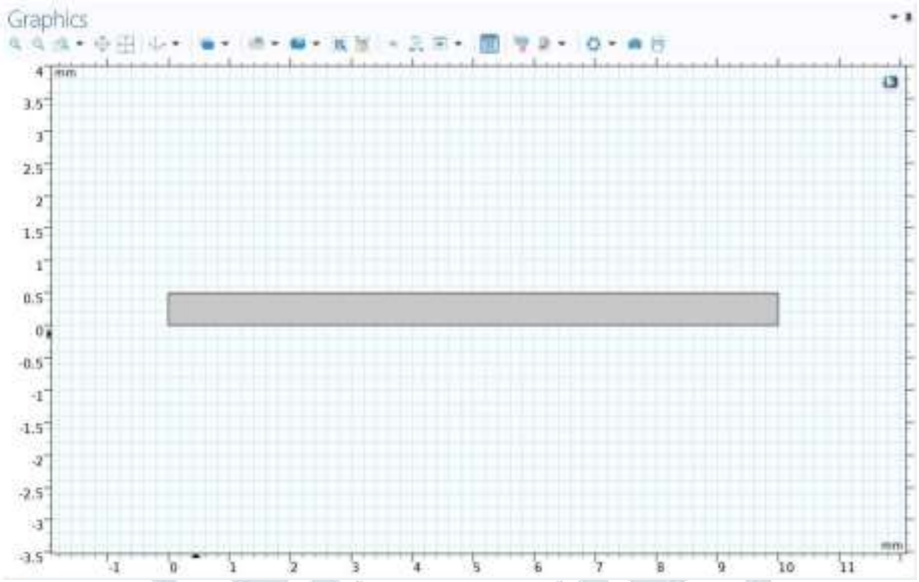

Figure 3: Graphical user interface of COMSOL multiphysics 5.6

V. RESULTS AND DISCUSSION

A harmonic force having 1N amplitude and 4Hz frequency is applied to the free end of the cantilever. The electric potential generated on application of the force is calculated by the COMSOL Multiphysics 5.6 software using finite element method. The time response of the generated electric potential in the top electrode with respect to the bottom electrode or ground is shown in Fig. 4. The applied stress and the electric potential distribution is shown in Fig. 5.

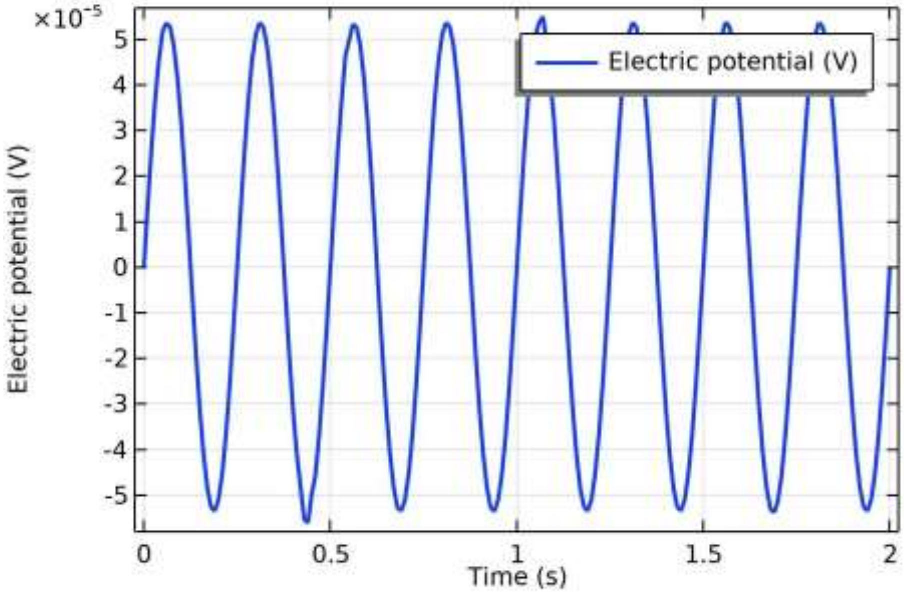

Figure 4: Time response of electric potential at the top electrode with respect to ground

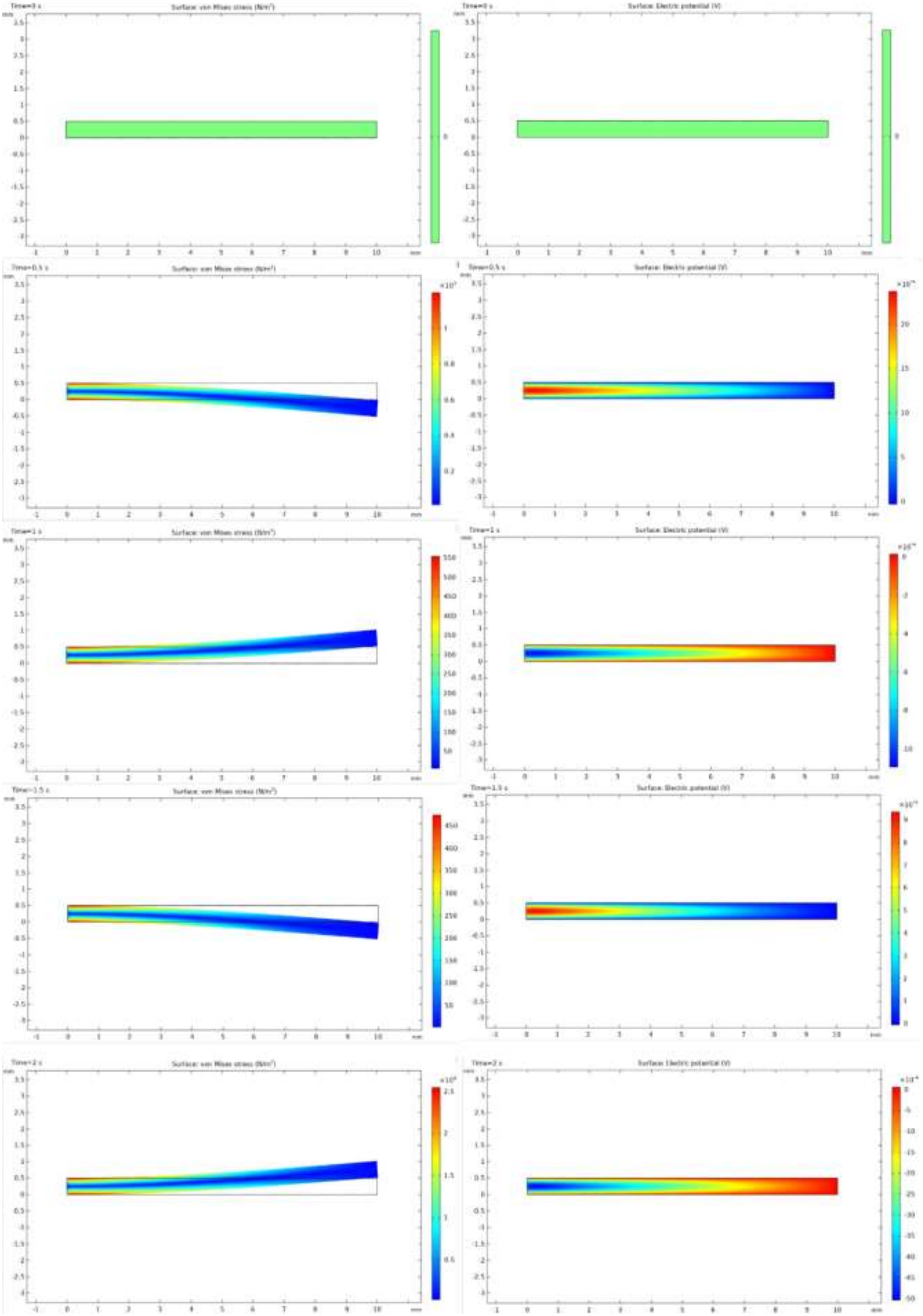

Figure 5: Applied stress and generated electric potential observed at an interval of 0.5 second

The values of the stress and electric potential acquired at an interval of 0.1 second between 0 and 2 second is tabulated in Table 1.

Table 1: Values of stress applied and generated electric potential acquired at an interval of 0.1s

TIME (S)	VON MISES STRESS (N/M^2)	TIME (S)	ELECTRIC POTENTIAL (V)
0	0	0	0
0.1	428849.3308	0.1	3.15E-05
0.2	693895.2368	0.2	-5.10E-05
0.3	693830.6082	0.3	5.10E-05
0.4	429924.5973	0.4	-3.16E-05
0.5	24.7195164	0.5	-1.55E-09
0.6	428837.9698	0.6	3.15E-05
0.7	695316.2989	0.7	-5.11E-05
0.8	694682.132	0.8	5.11E-05
0.9	430002.8165	0.9	-3.16E-05
1	11.53017922	1	6.85E-10
1.1	428855.8316	1.1	3.17E-05
1.2	693891.6555	1.2	-5.10E-05
1.3	694697.0014	1.3	5.11E-05
1.4	428853.4057	1.4	-3.15E-05
1.5	4.095288232	1.5	-7.21E-10
1.6	429684.2532	1.6	3.16E-05
1.7	697594.3368	1.7	-5.13E-05
1.8	694016.8241	1.8	5.10E-05
1.9	428724.3498	1.9	-3.15E-05
2	45.78728553	2	3.41E-09

Applied stress and generated electric potential calculated by COMSOL multiphysics 5.6 software are sampled at a constant rate and the sampled data is exported in an excel sheet. Identification of the system model of piezoelectric cantilever is done using the MATLAB system identification toolbox. To identify the system model of the piezoelectric cantilever different combinations of number of poles and zeros are assumed and the MATLAB program code is run. The estimated transfer functions along with the fit to estimation percentage for different combinations of poles and zeros are tabulated in Table 2.

Table 2: Estimated transfer function and fit to estimation percentage for different combination of poles and zeros

NO OF POLE	NO OF ZERO	FIT TO ESTIMATION PERCENTAGE	TRANSFER FUNCTION
2	0	98.29%	$\frac{1.248 \times 10^{-10}}{s^2 + 3.861 \times 10^{-09}s + 630.4}$
2	1	83%	$\frac{1.075 \times 10^{-09}s - 1.118 \times 10^{-09}}{s^2 + 4.525 \times 10^{-09}s + 634.4}$
2	2	83.11%	$\frac{6.452 \times 10^{-12}s^2 + 1.102 \times 10^{-09} - 2.741 \times 10^{-10}}{s^2 + 3.667 \times 10^{-09}s + 632.7}$
3	0	1.007%	$\frac{-1.162 \times 10^{-10}}{s^3 + 22.19s^2 + 15.62s + 334.3}$
3	1	98.29%	$\frac{-5.025 \times 10^{-08}s + 3.907 \times 10^{-08}}{s^3 + 578.6s^2 + 631.8s + 3.655 \times 10^{-05}}$
3	2	77.97%	$\frac{6.189 \times 10^{-10}s^2 + 2.051 \times 10^{-08}s - 2.443 \times 10^{-08}}{s^3 + 17.13s^2 + 652s + 1.088 \times 10^{-04}}$
3	3	86.35%	$\frac{6.992 \times 10^{-11}s^3 + 1.412 \times 10^{-09}s^2 + 2.666 \times 10^{-07}s - 1.332 \times 10^{-}}{s^3 + 101.7s^2 + 657.6s + 6.507 \times 10^{04}}$

VI. CONCLUSION

In this work the identification of a mathematical model of piezoelectric energy harvesting system is carried out. The objective of this work is to identify the mathematical model of piezoelectric energy harvesting system so that the equivalent circuit of the system can be found out using network synthesis technique. The equivalent circuit can be later used to find the responses of the device. After identification of the system, the model can be concluded that the piezoelectric cantilever energy harvesting system is a second order system having 2 poles and no zeros. The equivalent circuit of the system therefore can be represented easily as a series RLC circuit. In future the parameter of the equivalent circuit is to be determined.

REFERENCES

[1] S.P. Beeby, Z. Cao, A. Almussallam,11 - Kinetic, thermoelectric and solar energy harvesting technologies for smart textiles, Editor(s): Tünde Kirstein, In Woodhead Publishing Series in Textiles, Multidisciplinary Know-How for Smart-Textiles Developers, Woodhead Publishing, 2013 Pages 306-328, ISBN 9780857093424, https://doi.org/10.1533/9780857093530.2.306.

[2] Maryline Chetto, Audrey Queudet, 3 - Harnessing Ambient Energy for Embedded Systems, Editor(s): Maryline Chetto, Audrey Queudet, Energy Autonomy of Real-Time Systems, Elsevier, 2016, Pages 57-83, ISBN 9781785481253, https://doi.org/10.1016/B978-1-78548-125-3.50003-8.

[3] M. Lee, J. Bae, J. Lee, C.-S. Lee, S. Hong, Z.L. Wang, Self-powered environmental sensor system driven by nanogenerators, Energy Environ. Sci. 4 (2011) 3359–3363.

[4] C.F. Pan, Z.T. Li, W.X. Guo, J. Zhu, Z.L. Wang, Fiber-based hybrid nanogenerators for/as self-powered systems in biological liquid, Angew. Chem. -Int. Ed. 50 (2011) 11192–11196.

[5] S. Bai, Q. Xu, L. Gu, F. Ma, Y. Qin, Z.L. Wang, Single crystalline lead zirconate titanate (PZT) nano/micro-wire based self-powered UV sensor, Nano Energy 1 (2012) 789–795.

[6] C.F. Pan, W.X. Guo, L. Dong, G. Zhu, Z.L. Wang, Optical fiber-based core-shell coaxially structured hybrid cells for self-powered nanosystems, Adv. Mater. 24 (2012) 3356–3361.

[7] Y. Jie, N. Wang, X. Cao, Y. Xu, T. Li, X. Zhang, Z.L. Wang, Self-powered triboelectric nanosensor with poly(tetrafluoroethylene) nanoparticle arrays for dopamine detection, ACS Nano 9 (2015) 8376–8383.

[8] S. Lee, R. Hinchet, Y. Lee, Y. Yang, Z.H. Lin, G. Ardila, L. Montes, M. Mouis, Z. L. Wang, Ultrathin nanogenerators as self-powered/active skin sensors for tracking eye ball motion, Adv. Funct. Mater. 24 (2014) 1163–1168.

[9] G.-T. Hwang, H. Park, J.-H. Lee, S. Oh, K.-I. Park, M. Byun, H. Park, G. Ahn, C. K. Jeong, K. No, H. Kwon, S.-G. Lee, B. Joung, K.J. Lee, Self-powered cardiac pacemaker enabled by flexible single crystalline pmn-pt piezoelectric energy harvester, Adv. Mater. 26 (2014) 4880–4887.

[10] H.L. Zhang, Y. Yang, T.C. Hou, Y.J. Su, C.G. Hu, Z.L. Wang, Triboelectric nanogenerator built inside clothes for self-powered glucose biosensors, Nano Energy 2 (2013) 1019–1024.

[11] H. Zhang, Y. Yang, Y. Su, J. Chen, C. Hu, Z. Wu, Y. Liu, C.P. Wong, Y. Bando, Z. L. Wang, Triboelectric nanogenerator as self-powered active sensors for detecting liquid/gaseous water/ethanol, Nano Energy 2 (2013) 693–701.

[12] Y. Yang, H.L. Zhang, Y. Liu, Z.H. Lin, S. Lee, Z.Y. Lin, C.P. Wong, Z.L. Wang, Silicon-Based Hybrid Energy Cell for Self-Powered Electrodegradation and Personal Electronics, Acs Nano 7 (2013) 2808–2813.

[13] Y. Yang, H.L. Zhang, J. Chen, S.M. Lee, T.C. Hou, Z.L. Wang, Simultaneously harvesting mechanical and chemical energies by a hybrid cell for self-powered biosensors and personal electronics, Energy Environ. Sci. 6 (2013) 1744–1749.

[14] Y. Yang, H.L. Zhang, J. Chen, Q.S. Jing, Y.S. Zhou, X.N. Wen, Z.L. Wang, Single-electrode-based sliding triboelectric nanogenerator for self-powered displacement vector sensor system, Acs Nano 7 (2013) 7342–7351.

[15] Z.-H. Lin, G. Zhu, Y.S. Zhou, Y. Yang, P. Bai, J. Chen, Z.L. Wang, A self-powered triboelectric nanosensor for mercury ion detection, Angew. Chem. -Int. Ed. 52 (2013) 5065–5069.

[16] P. Lin, X. Yan, Z. Zhang, Y. Shen, Y. Zhao, Z. Bai, Y. Zhang, Self-powered UV photosensor based on PEDOT:PSS/ZnO micro/nanowire with strain-modulated photoresponse, ACS Appl. Mater. Interfaces 5 (2013) 3671–3676.

[17] A. Yu, P. Jiang, Z.L. Wang, Nanogenerator as self-powered vibration sensor, Nano Energy 1 (2012) 418–423.

[18] C. Xu, C.F. Pan, Y. Liu, Z.L. Wang, Hybrid cells for simultaneously harvesting multi-type energies for self-powered micro/nanosystems, Nano Energy 1 (2012) 259–272.

[19] White, N.M.; Glynne-Jones, P.; Beeby, S.P. (2001). "A novel thick-film piezoelectric micro-generator" (PDF). Smart Materials and Structures. 10 (4): 850–852. Bibcode:2001SMaS...10..850W. doi:10.1088/0964-1726/10/4/403.

[20] Kymissis, John (1998). "Parasitic power harvesting in shoes". Digest of Papers. Second International Symposium on Wearable Computers (Cat. No.98EX215). Second International Symposium on Wearable Computers. pp. 132–139. CiteSeerX 10.1.1.11.6175. doi:10.1109/ISWC.1998.729539. ISBN 978-0-8186-9074-7. S2CID 56992.

[21] Xu, J.; Tang, J. (23 November 2015). "Multi-directional energy harvesting by piezoelectric cantilever-pendulum with internal resonance". Applied Physics Letters. 107 (21): 213902. Bibcode:2015ApPhL.107u3902X. doi:10.1063/1.4936607. ISSN 0003-6951.

[22] ""Japan: Producing Electricity from Train Station Ticket Gates"". Archived from the original on 9 July 2007. Retrieved 18 June 2007.

[23] Powerleap tiles as piezoelectric energy harvesting machines "Energy Scavenging with Shoe-Mounted Piezoelectrics" (PDF). Archived from the original (PDF) on 9 April 2011. Retrieved 9 February 2010.

[24] Baker, Jessy; Roundy, Shad; Wright, Paul (2005). "Alternative Geometries for Increasing Power Density in Vibration Energy Scavenging for Wireless Sensor Networks". 3rd International Energy Conversion Engineering Conference. American Institute of Aeronautics and Astronautics. doi:10.2514/6.2005-5617. ISBN 978-1-62410-062-8.

[25] Xu, Jia Wen; Liu, Yong Bing; Shao, Wei Wei; Feng, Zhihua (2012). "Optimization of a right-angle piezoelectric cantilever using auxiliary beams with different stiffness levels for vibration energy harvesting". Smart Materials and Structures. 21 (6): 065017. Bibcode:2012SMaS...21f5017X. doi:10.1088/0964-1726/21/6/065017. ISSN 0964-1726.

[26] Goldschmidtboeing, Frank; Woias, Peter (2008). "Characterization of different beam shapes for piezoelectric energy harvesting". Journal of Micromechanics and Microengineering. 18 (10): 104013. Bibcode:2008JMiMi..18j4013G. doi:10.1088/0960-1317/18/10/104013. ISSN 0960-1317.

[27] Lennart Ljung, Torkel Glad, “Modeling of Dynamic Systems”, PTR Prentice Hall, ISBN: 9780135970973, 0135970970

[28] Lennart Ljung, “System Identification Theory For The User”, Pearson Education, ISBN: 9780132440530, 0132440539