Design and Modelling of a Piezoelectric Road Energy Harvester

Bin Wei
Department of Computer Science and Technology
Algoma University
Sault Ste Marie, Canada
Email: bin.wei@algomau.ca

Rahul Iyer
Department of Mechanical Engineering
University of Windsor
Windsor, Canada
Email: iyer112@uwindsor.ca

Abstract— **The physical model of a piezoelectric road energy harvester is successfully illustrated in this work. The principle governing the design of the piezoelectric elements of the harvester has been explained in detail. The design of the piezoelectric elements has been determined by various simulations in Matlab, and the plots of which have been represented thoroughly. Based on the Matlab results, a physical model of the piezoelectric energy harvester has been successfully designed using SolidWorks. The dynamic analysis of the harvester is used to elucidate the operation of the design. Finally, the stress and displacements plots are used to validate the proposed design of the piezoelectric road energy harvester.**

Keywords - piezoelectric; road energy harvester; modelling.

I. INTRODUCTION

With the increase in fossil fuel usage, the imminent depletion of non-renewable sources of energy and the negative costs associated with it occurred as a consequence of the overall ecology [1]. The need for environmentally friendly and renewable energy sources has been on the rise for the best part of the past two decades. While solar and wind energies have proved to be immensely promising in being able to suffice more applications than previously envisioned [2]-[5], their true potential remains untapped by some countries that cannot boast of the same geological advantages as comparing to others [6]. Consequently, to remedy some of these difficulties, kinetic energy harvesting has garnered tremendous attention in recent years aided by the advancements made in the field of piezoelectricity.

A popular application of kinetic energy harvesting using the principles of piezoelectricity is the piezoelectric road energy harvester. The idea is to utilize the wasted kinetic energy emanated by vehicles on the road (vibrations) by converting it to electrical energy which may be used for other applications. The ability of piezoelectric materials to generate electric potential when subjected to ambient vibrations has been well documented in numerous pieces of past research [7]-[9].Piezoelectric energy generation from kinetic energy can be obtained by two major approaches: the cantilever beam tactic and the impact-based approach.

Piezoelectric cantilever beams have been found to be highly sensitive to minute ambient vibrations, thus generating power at a small scale, making it a viable option for potentially powering low power motion sensors, radar systems and speed detectors [10]. While the previous study considered the use of the principle of impedance matching to maximize power output from the piezoelectric cantilever beams, studies considering the use of piezoelectric beams fixed at both ends [11] have shown to produce much larger deformations and thus, marginally improving the power output of the energy harvesting system. Moreover, the efficiency of these harvesters is heavily dependent on the speed of the vehicles on the road which indicated the scope for improvement in terms of frequency tuning for covering larger distances. Apart from the vehicle velocity analysis, other practical considerations such as the position of the harvester along particular length of road, as well as the effect of road surface irregularities on power generation of a piezoelectric road harvester has given rise to new perspectives with regards to improving the efficiency of such harvesting systems [12]. Cantilever beam based piezoelectric energy harvesters also offer numerous opportunities for further research with regards to altering its individual components, especially the tip mass. The use of a single tip mass for multiple piezoelectric cantilevers [13] illustrates a much simpler circuit structure as it eliminated the use of multiple rectifier circuits, as well as made the system behaviour more lucid as the cantilever oscillations became much more predictable. As a result, power estimation for the system is readily obtainable.

The scientific inquiry into piezoelectric road energy harvesters has also led to improvements being made in the digital space, wherein empirical data may be easily compared with digitally computed results from software packages [14] that are specially dedicated to analysing and accruing road, environmental and piezoelectric material data over numerous years and thus, providing an increased degree of validity, which can aid future applications. Various pieces of research have also focused on the materials most suitable to amass maximum energy from the road harvesters, with complex composite films providing one of the best results in this domain [15].

Apart from piezoelectricity, electromagnetic approaches that can convert kinetic energy into usable forms of electricity (as road harvesters) have also been studied extensively in the past [16]. Moreover, these approaches have been further extended into the mobile domain as opposed to the stationary domain (road harvesters) wherein the heat energy dissipated by vehicle suspension systems especially, the shock absorbers has been electromagnetically converted into electrical energy by incorporating regenerative shock absorbers [17].

In this paper, the aim is to evaluate the performance of an impact based piezoelectric energy harvester consisting of cylindrical piezoelectric elements that are embedded into a robust steel structure that can endure the forces exerted by various vehicles passing on the road, which is the main contribution of this study. The actuation of the harvester is done through a separate hydraulic mechanism [18] with minor changes, which transmits the forces exerted by the vehicles into a hydraulic piston, which then stresses the piezoelectric block to cause electricity generation.

The structure of the paper is organized as follows: Section 2 presents the principle of the piezoelectric road energy harvester; analysis of the proposed piezoelectric road energy harvester is conducted in Section 3; Section 4 illustrates the design process of the piezoelectric module; stress analysis of the piezoelectric road energy harvester is conducted in Section 5; and finally the conclusion is given in Section 6.

II. THE PRINCIPLE

The piezoelectric material has been used in the form of a transformer model [19] as shown in Figure 1:

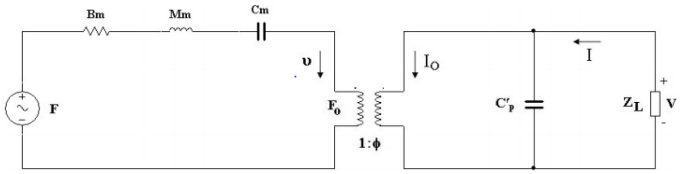

Figure 1. The piezoelectric generator transformer model

The transformer model illustrates two sides: the primary side and the secondary side. The primary side of the transformer uses the mechanical and dynamic properties of the piezoelectric material to model an analogous electrical representation, in which the damping constant of the piezoelectric material B_m is considered as a resistance, mass M_m as an inductor and the mechanical compliance C_m as a capacitor. The input source on the primary side is the input force F, which is induced mechanically. The resultant current on the primary side is the velocity of the piezoelectric layers caused due to the mechanical deformation corresponding to the applied force F. Fo represents the internal force responsible for the electrical energy generation on the secondary side of the transformer model.

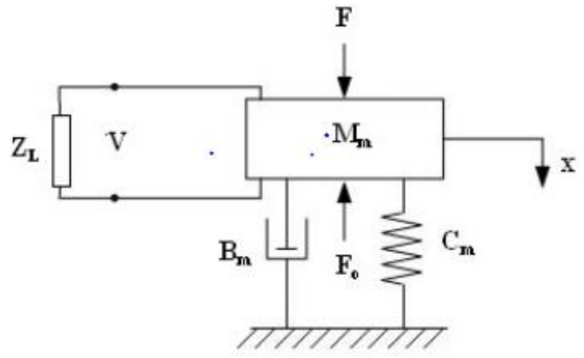

Figure 2. Mechanical realization of piezoelectric generator model

On the secondary side, Z_L represents the load connected to the piezoelectric model. C_P' is the blocked capacitance while V is the potential difference across the load Z_L. I is the resultant current generated while I_O is the current corresponding to the internal force Fo of the piezoelectric material. The mechanical realization of this model is shown in Figure 2.

III. ANALYSIS

The design of the piezoelectric cylinders is based on the simulations performed in Matlab. These simulations are performed taking the maximum possible force that can be exerted on the piezoelectric energy harvesting system into consideration, i.e., the force exerted by the weight of a loaded truck. The input force is in the form of two pulses, assuming that only the first two sets of wheels have passed over the piezoelectric energy harvesting system. Thus in theory, the bigger the vehicle, the larger is the power generated. However, the corresponding mechanical structure of the piezoelectric energy harvester has to be robust to endure the stresses exerted by such heavy vehicles, which will be discussed further in Section 5. The energy harvesting system considers six piezoelectric cells being embedded in one mechanical assembly.

A circular cross section for the piezoelectric material is deemed most appropriate for the piezoelectric energy harvester. This is because a cylindrical structure is much easier to manufacture for future mass production without incurring excessive production costs. The initial iterations take into consideration different diameters and thicknesses based on which power and voltage are calculated. For thickness ranging from 1 to 10 cm, the power plot is discontinuous as the curve would go back to zero soon after the first impact. Moreover, the plot for power generated for diameters ranging from 1 to 10 cm also shows tremendous variations. Hence, the thickness to area ratio is a critical factor in determining the optimum power generated, which is helpful in determining the dimensions of the piezoelectric cylinder.

The goal is to achieve sustained oscillations for the piezoelectric cylinder after impact in order to generate continuous power and thus facilitate continuous energy generation, which can later be used in various applications. Hence, further iterations are conducted by varying the thickness of the piezoelectric cylinder to up to 20 cm. The diameter of the cylinder is restricted to a value below 10 cm.

The most suitable results are obtained when the piezoelectric material is designed according to dimensions mentioned in Table 1, the result of which will be used to determine the resultant mean power over the time interval [0, 200] seconds.

TABLE 1. DIMENSIONS OF THE PIEZOELECTRIC CYLINDER

Diameter	6.5 cm
Thickness	18 cm

The resultant plots for input force, voltage and power generated versus time are shown in Figure 3.

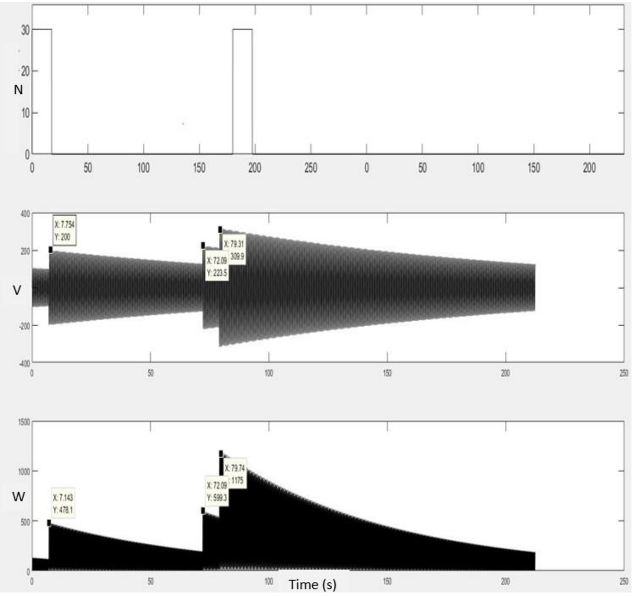

Figure 3. Input force, voltage, power versus time

The peak values obtained from Figure 4 for voltage and power at first impact are listed in Table 2.

TABLE II. RESULTANT PEAK VALUES FOR VOLTAGE AND POWER

Voltage	200 V
Power	478.1 W

According to the Table 1, the resultant mean power over the time interval [0, 200] seconds is also calculated as shown in Figure 4.

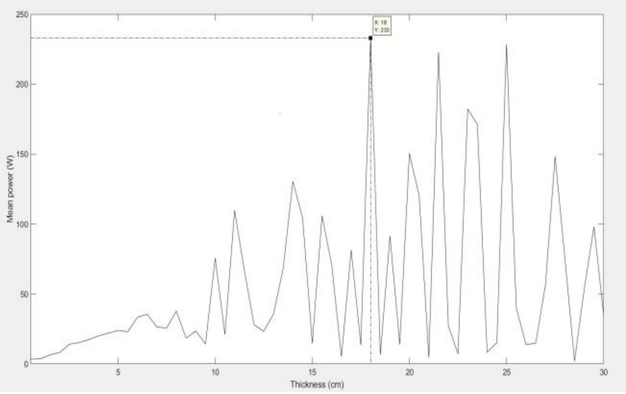

Figure 4. Calculation of mean power

Thus from Figure 4, it is clear that at thickness 18 cm, the mean power obtained is 233W. Further, using the optimization curve function in Matlab, Figure 3 is replotted to obtain the optimized values for power and voltage, which is shown in Figure 5 below.

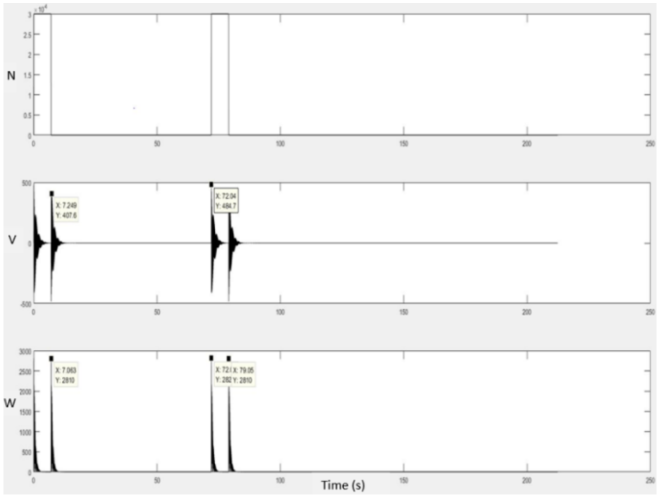

Figure 5. Optimized voltage and power versus time

TABLE III. RESULTANT PEAK VALUES FOR OPTIMIZED VOLTAGE AND POWER

Voltage	407.6V
Power	2810W

The optimized values of voltage and power after the first impact obtained from Figure 5 is shown in Table 3. For a value of maximum possible input force (weight of the vehicle), the corresponding power and voltage outputs are successfully calculated using Matlab.

IV. DESIGN OF THE PIEZOELECTRIC MODULE

The actual force exerted by the vehicle is a complex calculation owing to the effect of vehicle suspension systems and that of the module itself. The initial design of the piezoelectric road energy harvester are inclusive of a spring system which aided the movement of the pressuring plate back to its initial position. However, a problem identified with this design being that the tendency of the springs that causes an oscillating effect to the pressuring plate and thus, making the system unstable with poor feasibility. Consequently, a solution identified to this problem being that the inclusion of dampers so as to disintegrate the oscillations produced by the springs, and stabilize the spring back motion of the pressuring plate. Thus, the dynamic action of the entire system is more controlled with added protection offered to the piezoelectric cylinders through energy dissipation carried out by the dampers.

However, the power generation potential of the piezoelectric cylinders is predicated mainly on the impact-based approach of the pressuring plate caused by the movement of vehicles on the road. The inclusion of dampers causes the movement of the pressuring plate to slow down with the entire scenario liable to be analysed in a quasi-static state rather than an impulsive impact based state. This affects the power generation capacity of the piezoelectric cylinders.

The best solution to combat this problem is to make use of an embedded system of thick steel block and piezoelectric cylinders. The elasticity modulus of steel could be used favourably to perform the spring and damping action simultaneously. This of course, depends on the applied stress being within the elastic limit of the steel. Hence, it is imperative to design the steel block in a manner in which its height exceeded that of the piezoelectric cylinders. Due to this fact, the pressuring plate would first make contact with the steel during the impact while causing it to elastically compress and gradually exposing the piezoelectric cylinders to the input stress. This ensures the durability of the piezoelectric cylinders by preventing cracking and sudden buckling due to high value of the input stress (impulse). The proposed method thus advocates the use of cheap and easily available grade of steel, which can be easily replaced as part of planned and regular maintenance routines.

The grade of steel used for the steel block is AISI 304 stainless steel. This grade of stainless steel is the most commonly used and cheapest grade of steel available commercially. The material properties for AISI 304 stainless steel is shown in Table 4.

TABLE IV. PROPERTIES OF AISI 304 STAINLESS STEEL

	Physical properties	metric
1.	Density	8 g/cc
2.	Hardness B	70
3.	Ultimate tensile strength	505 Mpa
4.	Yield tensile strength	215 Mpa
5.	Modulus of elasticity	200 Gpa
6.	Poisson’s ratio	0.29
7.	Shear modulus	86 Gpa

The material used for the piezoelectric cylinders is PZT-5H. The material properties for PZT-5H is shown in Table 5.

TABLE V. MATERIAL PROPERTIES OF PZT-5H

1.	Density	7.4 g/cc
2.	D33	585e-12
3.	K33	0.59
4.	K(eff)	0.53
5.	Modulus of Rupture	61.5 MPa
6.	Damping Constant	5e-8

The selection of the PZT-5H material is based on the comparatively higher values of D33 (piezoelectric coefficient), K33 (piezoelectric coupling coefficient) and K(eff) (effective piezoelectric coupling coefficient) against the other grades of commercially available piezoelectric material [20]. The material PZT-5H is specifically picked considering the application used in this study.

4.1. Dynamics of the system

In order to calculate the acceleration of the piezoelectric bodies within the module when stressed by the vehicle above, it is essential to consider the following 2-DOF mass and spring damper system, as shown in Figure 6.

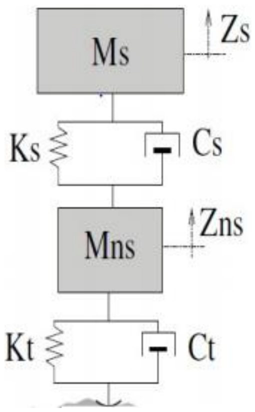

Figure 6. 2 DOF mass-spring-damper system

In Figure 6, Ms represents the mass of the vehicle while K_s and C_s resemble the spring constant and damping constant for its suspension system, respectively. Similarly, M_{ns} represents the combined mass of the piezoelectric cylinders within the module while K_t and C_t resemble its spring constant and damping constant, respectively.

The force exerted due to the vertical acceleration of the vehicle suspension system is the same force responsible for stressing the piezoelectric material within the module. The free body diagram of the two masses in the system yields the following two equations:

$$M_s \ddot{Z}_s = K_s(Z_{ns} - Z_s) + C_s(\dot{Z}_{ns} - \dot{Z}_s) \tag{1}$$

$$M_{ns} \ddot{Z}_{ns} = -K_t Z_{ns} - C_t \dot{Z}_{ns} - M_s \ddot{Z}_s \tag{2}$$

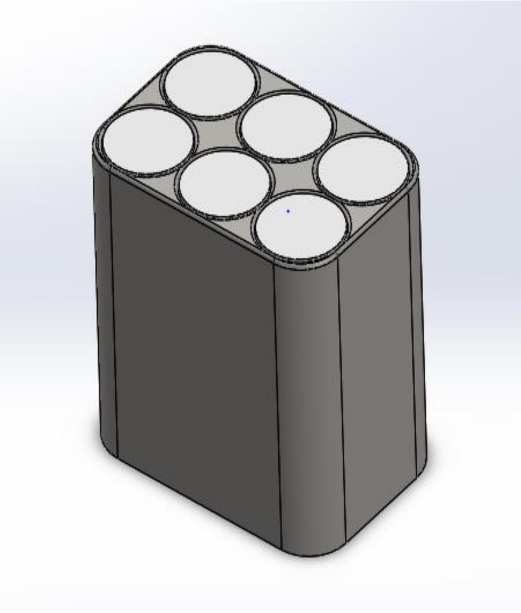

Figure 7. Piezoelectric energy harvester module

Thus, the acting force on the piezoelectric module depends on the vertical acceleration of the vehicle during motion. The module design is shown in Figure 7.

V. STRESS ANALYSIS OF HARVESTER

Stress analysis of the module was essential in determining the mechanical feasibility of the proposed design [21]. The acting force on the upper plate of the module was fixed as per the value discussed in the previous section. The stress analysis of the piezoelectric cylinders is as shown in Figure 8. From this dynamic analysis, it is shown that the stress exerted on the piezoelectric cylinder is approximately 0.8 MPa, which is less than the modulus of rupture for the PZT-5H material. Hence, the piezoelectric cylinders can be expected to operate as expected according to the calculations presented in the previous section.

Figure 9 represents the displacement plot for the piezoelectric cylinders under applied stress. Hence, the maximum displacement occurs at the upper layer of the piezoelectric cylinder with a value of approximately 2.4e-2 mm (as expected). The stress analysis of the steel block with the upper pressuring plate is as shown in Figure 10. The maximum stress experienced by the steel block is within the elastic limit of the material. Thus, the validity of the design is verified.

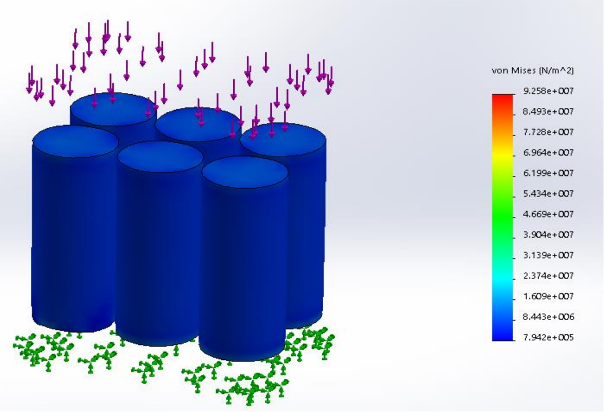

Figure 8. Stress analysis for piezoelectric cylinders

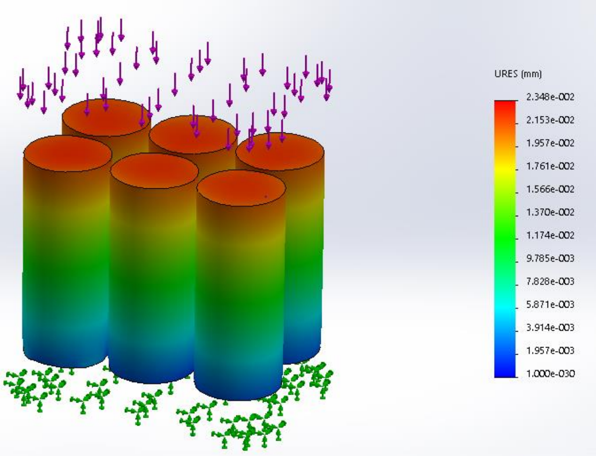

Figure 9. Displacement plot for piezoelectric cylinders

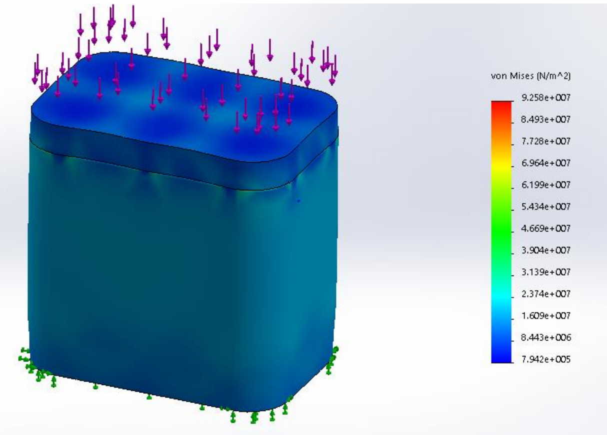

Figure 10. Stress plot for steel block with upper plate

VI. CONCLUSION

The material selections for the steel block and the piezoelectric cylinders are justified according to the method of application desired. The piezoelectric cylinders are designed according to the value of the input force (weight of the vehicle). For a value of maximum possible input force (weight of the vehicle), the corresponding power and voltage outputs are successfully calculated using Matlab. The average power over the time interval [0, 200] seconds, as a result of this design is theoretically obtained to be close to 233W, which is larger than that of the previous attempts. The design of the energy harvester is successfully validated via stress analysis in SolidWorks. The actual calculation for input force is successfully illustrated in Section 4 of this study. The expected price of the proposed energy generator is approximately $550 and the expected life of the proposed device is about 5 years. Future work will focus on a proposition of installation method of converter in real situation, which can hold much more load.

REFERENCES

[1] J. Szargut, A. Ziebik, and W. Stanek, “Depletion of the non-renewable natural exergy resources as a measure of the ecological cost”, Energy Conversion and Management, Vol. 43, pp. 119-1163, 2002.

[2] N. Papamanolis N, “An overview of solar energy applications in buildings in Greece”, International Journal of Sustainable Energy, Vol. 35, no. 8, pp. 814-823, 2016.

[3] A. Jamar, Z. Majid, W. Azmi, M. Norhafana, and A. Razak, “A review of water heating system for solar energy applications”, International Communications in Heat and Mass Transfer, Vol. 76, pp. 178-187, 2016.

[4] C. Abbey and G. Joos, “Supercapacitor Energy Storage for Wind Energy Applications”, IEEE Transactions on Industry Applications, vol. 43, no. 3. pp. 769 – 776, 2007.

[5] L. Mishnaevsky, “Composite materials for wind energy applications: micromechanical modelling and future directions”, Computational Mechanics, vol. 50, no. 2, pp. 195-207, 2012.

[6] R. Pravalie, C. Patriche, and G. Bandoc, “Spatial assessment of solar energy potential at global scale. A geographical approach”, Journal of Cleaner Production, vol. 209, pp. 692-721, 2019.

[7] C. Li, B. Li, X. Yang, and M. Meng, “Finite element analysis of a novel piezoelectric arch energy harvester”, 2015 IEEE International Conference on Information and Automation, Lijiang, China, pp. 2749-2754, 2015.

[8] C. Yang, Y. Song, M. Woo, J. Eom, J. Song, J. Kim, T. Lee, J. Choi, and T. Sung, “Feasibility study of impact-based piezoelectric road energy harvester for wireless sensor networks in smart highways”, Sensors and Actuators A: Physical, vol. 261, pp. 317-324, 2017.

[9] S. Gareh, B. Kok, C. Uttraphan, K. Thong, and A. Borhana, “Evaluation of piezoelectric energy harvester outcomes in road traffic applications”, in IET Clean Energy and Technology Conference, Kuala Lumpur, Malaysia, pp. 1-5, 2016.

[10] Y. Song, C. Yang, S. Hong, S. Hwang, J. Kim, J. Choi, S. Ryu, and T. Sung, “Road energy harvester designed as a macro-power source using the piezoelectric effect”. International Journal of Hydrogen Energy, vol. 41, pp. 12563-12568, 2016.

[11] H. Yang, L. Wang, Y. Hou, and M. Guo, “Development in stacked-array-type piezoelectric energy harvester in asphalt pavement”, Journal of Materials in Civil Engineering, vol. 29, no. 11, p. 04017224, 2017.

[12] Z. Zhang, H. Xiang, and Z. Shi, “Theoretical Modelling on Piezoelectric Energy Harvesting from Bridges Considering Roadway Surface Irregularities”, In Transportation Research Congress 2016: Innovations in Transportation Research Infrastructure, Reston, VA: American Society of Civil Engineers, pp. 673-684, 2016.

[13] Y. Song, C. Yang, S. Hwang, J. Kim, and T. Sung, “Design of Road Energy Harvester with Multiple Piezoelectric Cantileve Beams and a Single Tip Mass”, in 5th International Conference on Renewable Energy Research and Applications, Birmingham, UK, pp. 12563-12568, 2016

[14] F. Jiménez, M. Rodriguez, D. Alnoso, and J. Frutos, “Virtual instrument to obtain an optimal linear model for piezoelectric elements involved in road traffic energy harvesting”, Computer Standards and Interfaces, vol. 51, pp. 1-13, 2017.

[15] V. Vivekananthan, N. Alluri, Y. Purusothaman, A. Chandrasekhar, and S. Kim, “A flexible, planar energy harvesting device for scavenging road side waste mechanical energy via the synergistic piezoelectric response of K0.5Na0.5NbO3-BaTiO3/PVDF composite films”, Nanoscale, The Royal Society of Chemistry, pp. 15122-15130, 2017.

[16] Z. Zhang, X. Zhang, Y. Rasim, C. Wang, B. Du, and Y. Yuan, “Design, modelling and practical tests on a high-voltage kinetic energy harvesting (EH) system for a renewable road tunnel based on linear alternators”, Applied Energy, vol. 164, pp. 152-161, 2016.

[17] M. Abdelkareem, L. Xu, M. Ali, A. Elagouz, J. Mi, S. Guo, Y. Liu, and L. Zuo, “Vibration energy harvesting in automotive suspension system: A detailed review”, Applied Energy, vol. 229, pp. 672-699, 2018.

[18] T. Ching, D. Tsai, and C. Hsiao, “Developing a mechanical roadway system for waste energy capture of vehicles and electric generation”, Applied Energy, vol. 92, pp. 1-8, 2012.

[19] S. Platt, S. Farritor, and H. Haider, “On Low-Frequency Electric Power generation with PZT ceramics”, ASME Transactions on Mechatronics, vol. 10, no. 2, pp. 240-252, 2005.

[20] M. Hooker, “Properties of PZT-Based Piezoelectric Ceramics Between-150 and 250°C”, National Aeronautics and Space Administration, CR-1998-208707 report, 1998.

[21] D. Zhang and B Wei, “Interactions and optimizations analysis between stiffness and workspace of 3-UPU robotic mechanism”, Measurement Science Review 17.2, pp. 83-92, 2017.