Asian Journal of Scientific Research

ISSN 1992-1454

OPEN ACCESS Asian Journal of Scientific Research

ISSN 1992-1454
DOI: 10.3923/ajsr.2016.160.166

Research Article
Design and Analysis of a T-shaped Piezoelectric Cantilever Beam at Low Resonant Frequency using Vibration for Biomedical Device

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Abstract
Background: Ambient vibration energy can be converted into electrical energy in an energy harvester system by using three mechanisms; piezoelectric, electrostatic and electromagnetic. Among three mechanisms, piezoelectric mechanism is most efficient. In this mechanism, mechanical stress and strain generation of piezoelectric materials can be converted into electrical energy by ambient vibration energy for low power electronic system. To implement a piezoelectric energy harvester system from ambient vibration, a lower range of frequency will be chosen. To achieve the lower resonant frequency and higher stress of energy harvester, a cantilever beam is suitable because of its least stiff structure. **Materials and Methods:** The structural properties of a T-shape piezoelectric cantilever beam was analysed for piezoelectric energy harvesting mechanism. The 3-D geometry of the beam has been design using solid works. After that the simulation of the T-shaped piezoelectric cantilever beam has been performed by using Finite Element Analysis (FEA) in COMSOL multiphysics. In FEA simulation, the volume of the beam was considered 24.566×10^{-3} cm^3 under a vibration source of 0.5 g acceleration. **Results:** As a result, the beam was resonated at a frequency of 229.25 Hz. During resonance, free end of the beam has displaced the maximum 2.77 mm with RMS velocity of 3.29 m sec^{-1}. Finally, maximum stress of 2.39×10^8 N m^{-2} has found near the fixed end of the beam. **Conclusion:** This designed and analysed T-shaped piezoelectric cantilever beam will be suitable for scavenging and converting ambient low vibration energy into electrical energy for biomedical devices. The shape of the cantilever beam was designed as T-shape. In the design, complexity of the beam was reduced and no proof mass was used at the free end of the beam. After the analysis of the beam, a lower resonant frequency of 229.25 Hz was achieved compared to past researchers studies.

Key words: T-shaped cantilever, piezoelectric materials, FEA, ambient vibration, resonant frequency, energy harvesting, stress, biomedical device

Received: April 13, 2016 Accepted: August 16, 2016 Published: September 15, 2016

Citation: Md. Naim Uddin, Md. Shabiul Islam, Jahariah Sampe, M.S. Bhuyan and Sawal H. Md. Ali, 2016. Design and analysis of a T-shaped piezoelectric cantilever beam at low resonant frequency using vibration for biomedical device. Asian J. Sci. Res., 9: 160-166.

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Competing Interest: The authors have declared that no competing interest exists.

Data Availability: All relevant data are within the paper and its supporting information files.

INTRODUCTION

Energy harvesting is a unique way to generate energy from ambient energy. Harvesting energy from the environment is a promising alternative to batteries[1,2]. Harvested energy is aimed to provide power to small-scale and low-power electronics device such as wireless sensor networks, implantable medical devices and MEMS devices. So, it can be used to recharge or even replace batteries for autonomous microsystems[3]. There are various ambient energy sources which can be converted to the useable form of energy. In general, energy sources for energy harvesting devices are mechanical, thermal, light, winds and chemical etc.[1].

Mechanical strain and stress developed by deformation of smart structure can be used into energy harvesting devices. This movement displace the smart structure from its original position and can be converted to electrical energy using three mechanisms: Piezoelectric, electrostatic and electromagnetic[4-9]. Among those conversion mechanisms, piezoelectric mechanism have great promise and interest[10]. Piezoelectric cantilever beam has attained most attention due to its flexibility, lower resonant frequency and high stress generation. Lower frequencies (<1000 Hz) are found from ambient mechanical vibration sources[5]. A number of researches have been carried out on piezoelectric cantilever in the range of ambient mechanical vibration sources[6,11-15]. Ambient mechanical vibration of a piezoelectric cantilever can also be generated using fluid flow as shown in Fig. 1. In block-1, an analytical model will be developed based on vibration to get dimensions (length, width and height) of the cantilever with proof mass. In bolck-2, the piezoelectric energy harvester system can use wind, water and blood as an input sources of ambient fluid flow. In block-3, input sources of ambient fluid flow can be used to generate flow induced vibration. During fluid flow, Kármán Vortex street is responsible for generating pressure fluctuation along the piezoelectric cantilever beam. Because fluid flow was induced by putting a bluff body in front of the beam as shown in Fig. 2. In block-4, the beam will be in vibration mode due to the pressure fluctuation along the piezoelectric cantilever beam. As a result, stress will be obtained from the cantilever beam. It is known from piezoelectric effect that charge density is proportional to the stress. After that, in block-5 electrical energy will be obtained from the energy harvesting system due to piezoelectric effect. Here, the optimised electrical energy from block-5 will be integrated with the additional electrical circuit components (i.e., power management and energy storage) and finally applied to the load.

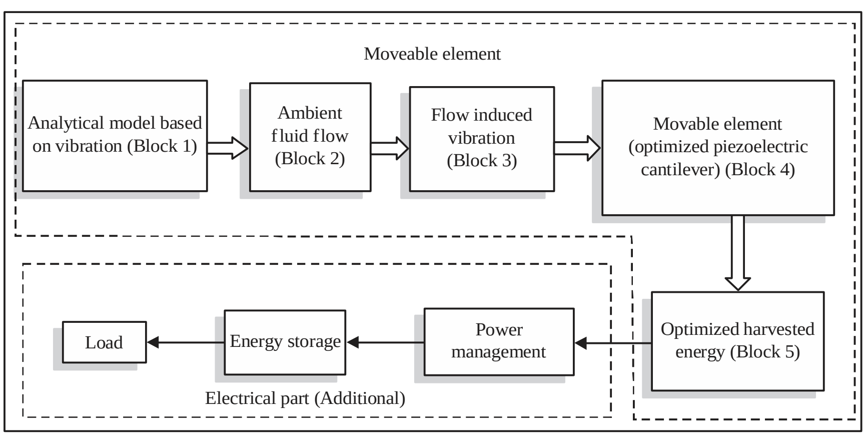

Fig. 1: Proposed block diagram of the piezoelectric energy harvester system using FIV, FIV: Flow induced vibration[16]

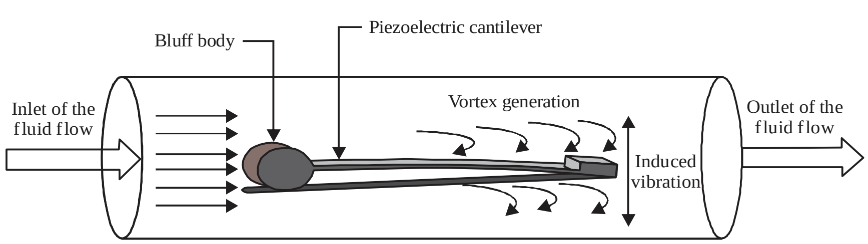

Fig. 2: An expected schematic of a piezoelectric energy harvesting system using FIV, FIV: Flow induced vibration[16]

In this study, a T-shaped piezoelectric cantilever beam has been designed in which PZT-5H was used as the piezoelectric materials and copper was used as a substrate. The model of the cantilever beam was based on vibration. Mechanical structural properties have been analysed using COMSOL multiphysics. Resonant frequency, stress development, displacement, velocity and total elastic energy of the structure have been obtained using a vibration source with an acceleration of 0.5 g. The resonant frequency of the designed beam was found at 229.25 Hz.

MATERIALS AND METHODS

Piezoelectric mechanism: In the piezoelectric mechanism, if piezoelectric material is physically deformed by pressure, vibration or force then it will create induced electrical field. In contrast, if electrical energy is applied then mechanical deformation will induce[4,17]. The electrical charge density generated by the piezoelectric cantilever can be calculated by using the following piezoelectric constitutive Eq. 1:

$$D_3 = d_{31}T_1 + \varepsilon_{33}^T E_3 \quad (1)$$

where, D_3 is the electrical charge density, d_{31} is the piezoelectric strain constant, T_1 is stress generated in the length direction of the piezoelectric layer, ε_{33}^T is the dielectric constant of the piezoelectric material under constant stress conditions and E_3 is the electric field developed in the "3" direction[18]. So, charge density is proportional to the developed stress from the as shown in Eq. 1.

Finite element analysis: To perform the FEA simulation, a design (1-D, 2-D or 3-D) of a geometry is required. In this study, a T-shaped cantilever beam was designed. The structure of the T-shape cantilever beam was made of piezoelectric material on a substrate. The PZT-5H was used as piezoelectric material and copper was used as a substrate. The design of the T-shaped cantilever beam was performed by solid works. At first, 2-D design for both PZT-5H and copper was performed separately as shown in Fig. 3a and b, respectively. After that, 3-D design for both PZT-5H and copper was carried out separately. Finally, assembly operation has been performed to assemble PZT-5H on copper substrate as shown in Fig. 3c. The experimental dimensions for the cantilever beam is shown in Table 1. According to the dimensions as shown in Table 1, the volume of the beam is 24.566×10^{-3} cm^3.

Table 1: Dimensions of the T-shaped cantilever beam

Cantilever elements	Length (mm)	Width (mm)	Thickness (mm)
Substrate (Copper)	5+13 = 18	8.64	0.15
Piezoelectric materials (PZT-5H)	5+8 = 13	8.64	0.065
Neck	5	3.00	0.215

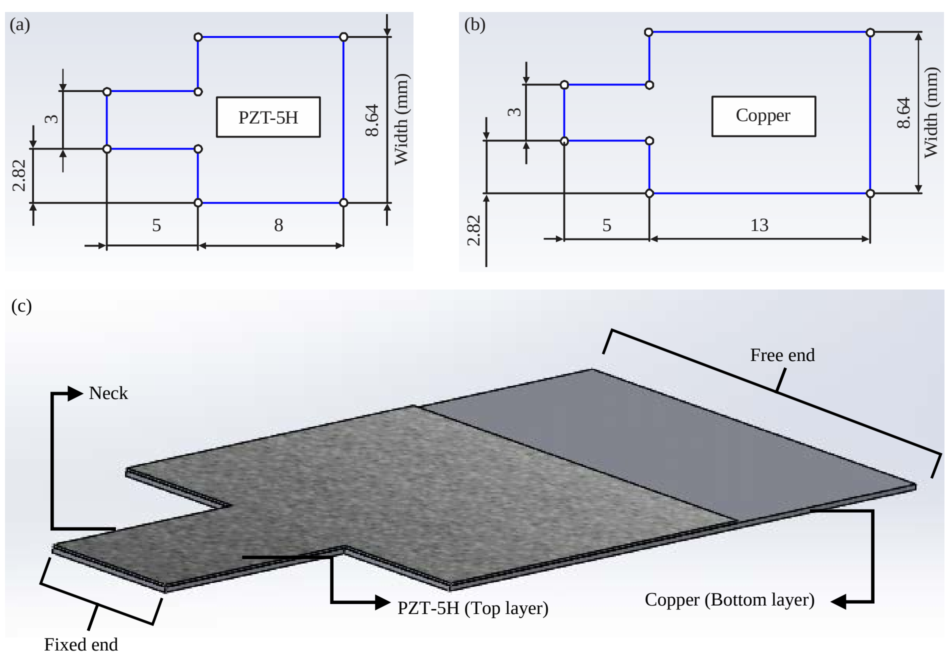

Fig. 3(a-c): (a) 2-D drawing for piezoelectric materials (PZT-5H), (b) 2-D drawing for substrate material (Copper) and (c) 3-D representation of T-shaped cantilever beam

After completion of the 3-D geometry design using SolidWorks, the 3-D model of the T-shaped cantilever beam has been imported to the COMSOL multiphysics for performing FEA simulation. At first, material properties for the PZT-5H and copper was assigned to the imported geometry as shown in Table 2. So that, T-shaped beam will be showed its mechanical properties (stress, strain, reaction force, displacement and velocity) according to the material properties of the assigned PZT-5H and copper. Then solid mechanics model has been used to assign boundary condition for the beam. During boundary condition set up of the T-shaped beam, one end was fixed and the other end was freed to vibrate as shown in Fig. 3c. Mechanical damping was set 0.001 for both PZT-5H and copper layer. The beam was kept at an acceleration vibration sources of 0.5 g. After that physics-controlled mesh with fine element size has been performed for the beam. The complete mesh has consisted of 42367 domain elements, 22795 boundary element and 858 edge element. Finally, the frequency domain analysis has conducted in a range of 210-242 Hz.

Table 2: Materials properties of the PZT-5H and copper

	Materials	
Properties	PZT-5H	Copper
Young's modulus	62×10^{9} Pa	120×10^{9} Pa
Poisson's ratio	0.31	0.34
Density	7500 kg m^{-3}	8960 kg m^{-3}

RESULTS AND DISCUSSION

Resonant frequency have a great impact on structure to design a piezoelectric cantilever beam. A cantilever shows one of the least stiff structure. As a result, it offers lower resonant frequency and larger stress and strain within a given volume. During resonance, the value of parameters such as displacement, velocity, stress and strain of structures will be maximum. For developing an energy harvesting device from ambient vibration, lower resonant frequency and higher stress of the cantilever beam structure will be desired.

In this study, the T-shaped cantilever beam was fixed at one end and the other end is free to vibrate. Smaller width side of the beam was fixed to reduce the resonant frequency. Resonant frequency at 229.25 Hz has been observed in a range of frequency domain 210-242 Hz with a vibration acceleration of 0.5 g in the displacement and RMS velocity magnitude curve as shown in Fig. 4a and b, respectively. The displacement and RMS velocity magnitude is zero at the fixed end with respect to the frequency range of 210-242 Hz. But displacement and Root Mean Square (RMS) velocity magnitude of the free end gradually increased and sharply

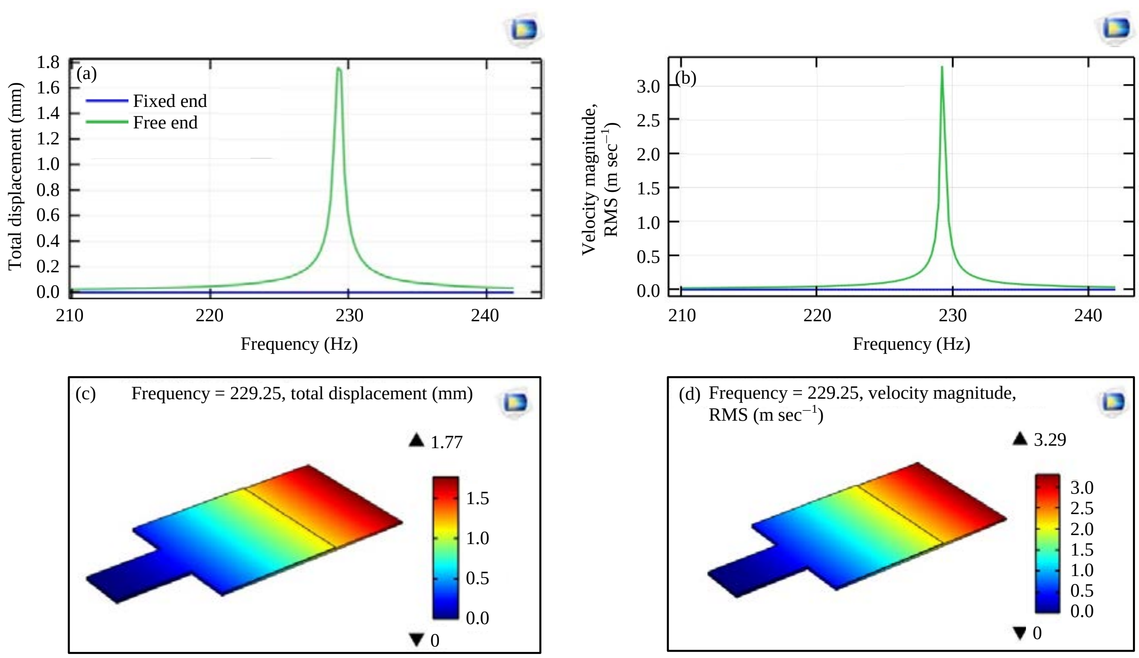

Fig. 4(a-d): (a) Displacement of the cantilever beam in the range of 210-242 Hz, (b) RMS velocity amplitude of the cantilever beam in the range of 210-242 Hz, (c) Displacement contour of the beam at 229.25 Hz and (d) RMS velocity magnitude contour of the beam at 229.25 Hz

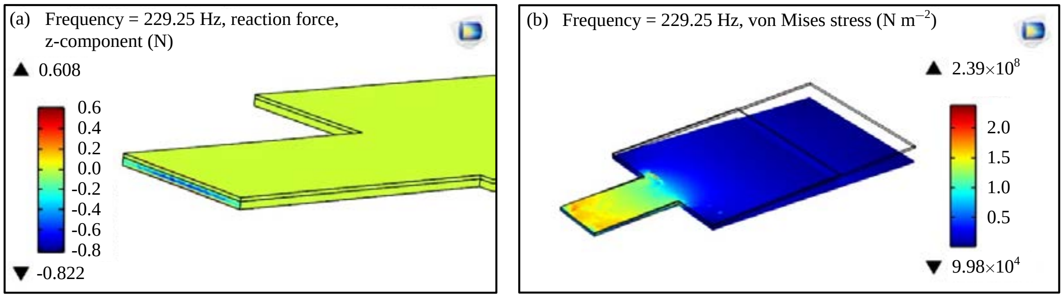

Fig. 5(a-b): (a) Reaction force, z-component (vertical) at fixed end of the cantilever beam and (b) Stress development contour of the cantilever beam

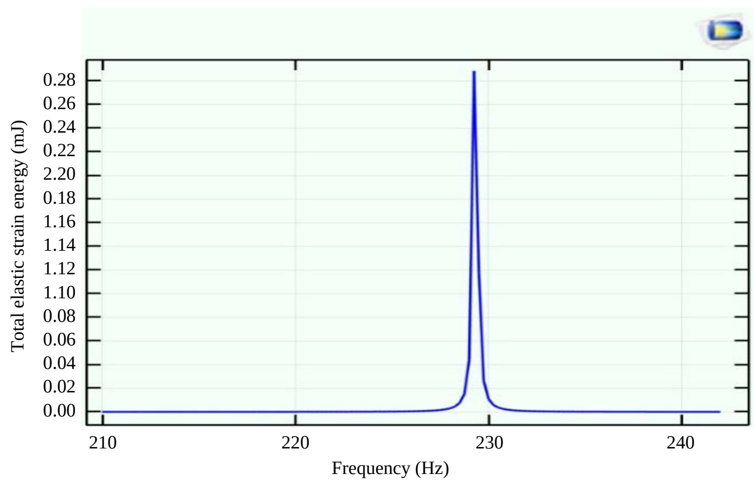

Fig. 6: Total elastic strain energy of the cantilever beam at the frequency range of 210-242 Hz

reach maximum up to 1.77 mm and 3.29 m sec^{-1}, respectively at 229.25 Hz. After that displacement and RMS velocity values gradually decreased. Due to the resonance at 229.25 Hz, the colour contour with scale of that maximum displacement and RMS velocity magnitude of the beam have been shown as in the Fig. 4c and d.

In addition, z-component (vertical component) of reaction force has been obtained at fixed surface as shown in Fig. 5a. It was shown that the range of vertical reaction force at fixed surface was -0.822 to 0.608 N. Here negative value of 0.822 N means that this amount of reaction force acting downward, while positive 0.608 N acting upward (vertical) z-direction. Moreover, compressive and tensile stress have been experienced by the piezoelectric materials due to the vibration as shown in Fig. 5b. From the observation, the maximum stress was obtained near the fixed end and minimum stress at the free end of the beam. The amount of minimum and maximum stress was 9.98×10^4 and 2.39×10^8 N m^{-2}, respectively. From the piezoelectric Eq. 1, that electrical charge density will be maximum where stress will maximum. For this reason, maximum charge will be found near the fixed end.

Based on our experimental observation in COMSOL multiphysics, the value of maximum total elastic strain energy was achieved approximately 0.28 mJ, as shown in Fig. 6. At the resonant frequency of 229.25 Hz with a vibration acceleration of 0.5 g.

The mechanical properties such as displacement, velocity, stress and strain analysis denoted to know the physical conditions of the cantilever beam. Displacement and velocity analysis has given the information that the movement at fix end of the beam was zero as shown in Fig. 4a and b. Furthermore, the upward and downward reaction force was also investigated as shown in Fig. 5a. As a result, it has observed that the beam will not tear away from the structure at which point the beam is fitted. The stress analysis indicated to find out magnitude and location of maximum and minimum stress at resonant frequency as shown in Fig. 5b.

Table 3: Comparison among the past researchers study and present study on the basis of resonant frequency, acceleration and proof mass

References	Resonant frequency (Hz)	Acceleration (1 g = 9.81 m sec^{-2})	Piezoelectric material	Proof mass
Jagtap and Paily[6]	630.00	1	ZnO	Pt
Blystad *et al.*[11]	500.00	0.25, 4.0	AlN	Si
Liu *et al.*[12]	650.00	1	PZT	Not used
Fang *et al.*[13]	608.00	1	PZT	Ni
Kim *et al.*[14]	243.00	0.5	PZT	Si
Park *et al.*[15]	528.00	0.39	PZT	Si
Shen *et al.*[19]	461.15	2	PZT	Si
Present study	229.25	0.5	PZT	Not used

So, that, the location and magnitude of charge density on the piezoelectric layer will be easy to find out which is proportional to the stress generation. As the free end of the beam has deformed from its original position so that the beam was in compression and tensile mode. Consequently, potential mechanical elastic strain energy has been generated in the beam as shown in Fig. 6.

Here, comparison among the past researchers study[6,11-15,19] and present study on the basis of resonant frequency, vibration sources of acceleration and proof mass is shown in Table 3. Energy harvesting devices had been designed by past researchers with different values of vibration sources. Maximum amount of electrical energy had been extracted from their energy harvester devices at resonant frequency. Resonant frequencies for their devices had been analysed and achieved from the ambient vibration sources. The cited resonant frequencies in Table 3 for energy harvesting devices was higher than the present studies. Moreover, some vibration sources of acceleration used by those cited works was higher compared to the present study. In addition, proof mass had been used by some researchers to reduce resonant frequency of their devices. But in the present study, no proof mass has been used to reduce resonant frequency nevertheless it showed minimum resonant frequency and avoid complexity in the 3-D geometry. The reduction of resonant frequency to 229.25 Hz with ambient vibration source of acceleration at 0.5 g for an energy harvesting device without proof mass posed a challenge. Because the beam can be mechanically resonated which is tuned at lower ambient vibration. In another study Liu *et al.*[12], ambient wind flow with a velocity of 15.6 m sec^{-1} was used as a vibration source to their micro-cantilever. But during initial characterization, the beam was in vibration mode with an acceleration of 1 g which is equivalent to turbulence induced vibration by 11.7 m sec^{-1} wind speed[12]. The dimension (i.e., length, width and thickness) and mass per unit length of a cantilever beam play a vital role in the resonant frequency of its structure[19]. The dimension of presented cantilever beam is much higher than the compared research works[6,11-15,19]. So, the presented T-shaped cantilever beam has higher surface area and volume. Consequently energy density for this cantilever will be higher.

CONCLUSION

In this study, a T-shaped piezoelectric cantilever beam has been presented, upon which FEA has been performed. Without using proof mass on the T-shaped beam, the resonant frequency of 229.25 is less than the other cited resonant frequency of the harvester. After the analysis of the T-shaped cantilever beam, mechanical properties such as stress, elastic strain energy, displacement and velocity with respect to frequency spectrum was obtained. The amount of maximum stress and total elastic strain energy was found 2.39×10^{8} N m^{-2} and 0.28 mJ, respectively. Maximum displacement and RMS velocity of the beam at its free end was obtained 1.77 mm and 3.29 m sec^{-1}, respectively. The peak values of mechanical properties were found at resonant frequency. In future, this T-shape beam can be used for generating electrical energy for low-power electronic devices such as wireless sensor, structural monitoring, machining-condition and medical monitoring etc.

SIGNIFICANCE STATEMENTS

- In piezoelectric mechanism, mechanical stress on piezoelectric materials can be converted into electrical energy
- Mechanical stress can be produced by applying forces on substances. That force can be generated by environmental ambient vibration (i.e., body movement of human beings or animals, fluid flow at artificial kidney, bridges and tall buildings etc.). In this study, the analyzed beam vibration is in the range of ambient vibration (<1000), moreover it is lower than the cited resonant frequency

- Human/animal body movement can produce potential vibration which can be used to power up wireless sensors to monitor patients/wild animal
- Flow induced vibration (blood/liquid used in artificial kidney) on piezoelectric materials can be used to power up or recharge the power system of artificial kidney

ACKNOWLEDGMENT

The authors gratefully acknowledge that this study was financially supported by UKM, through the grant funded under GUP 2014-023.

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