JOURNAL OF MECHANICAL ENGINEERING AND SCIENCES (JMES)
ISSN: 2289-4659 e-ISSN: 2231-8380
VOL. 15, ISSUE 1, 7754 – 7761
DOI: https://doi.org/10.15282/jmes.15.1.2021.11.0611

ORIGINAL ARTICLE

Performance comparison between dual cantilevered and touch based hybridized triboelectric harvesters

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ABSTRACT – The demand for energy harvesting technologies has been increasing over the years attributed to its significance to low power applications. One of the key problems associated with the vibration-based harvester is the fact that these harvesters generate low usable power while maximum peak power can only be attained when the device frequency matches the source frequency. In this study, triboelectric mechanism was investigated in combination with the piezoelectric mechanism in order to enhance the performance of the harvester. Triboelectric mechanism functions in a way that two dissimilar materials were placed in contact and then separated in order to generate surface charges and electric potential between them. Main design factors such as materials, surface area, structure, effective length, and etc. play a significant part in the enhancement of the performance. This study proposed two distinct designs of dual cantilevered structure and touch-based triboelectric energy harvester and evaluated the efficiency of the output between both structures. In addition, the effect of extension and surface area of triboelectric materials was investigated while the influence of these factors on the performance of the harvester was evaluated. The highest value of peak power obtained for dual cantilevered hybrid harvester was 650 µW across a load of 160 kΩ and frequency of 26 Hz. On the other hand, touch-based energy harvester produced an output peak power of 1220 µW across a load of 400 kΩ at 25 Hz. Achieving these power outputs may be able to power up electronics such as smartwatches, hearing aid and etc. Future studies on reliable low power applications to further advance the green power technology will be investigated.

ARTICLE HISTORY
Received: 20th June 2020
Revised: 20th Feb 2021
Accepted: 24th Feb 2021

KEYWORDS
Vibration; triboelectric; piezoelectric; hybridized; cantilevered

INTRODUCTION

Energy harvesting has been a sustainable energy solution and creating a system with high energy efficiency is required in the current highly progressing world. In this study, energy harvesting by means of vibration via a hybrid cantilevered triboelectric energy harvester and a touch-based hybrid triboelectric harvester was performed, analyzed, and evaluated for low power application systems. Various other transduction methods have been previously proposed such as piezoelectric [1], electrostatic [2], electromagnetic [3] and etc. However, in the triboelectric mechanism, the electric potential is generated as a result of surface charge formation during the contact and separation of two dissimilar materials. This mechanism can be executed at various approaches such as contact-separation mode [4], sliding mode [5], freestanding mode [6], and single electrode mode [7]. These modes can be applied in order to harvest energy from variety of energy sources including mechanical vibration, hydro, human motion, wind, and others. In addition, a device that utilized triboelectric mechanism can be prepared in variety of structures depending on the sources of energy that is required to be extracted. These structures are known as arch-shaped [8], cantilevered [9], spring-mass model [10], disc-shaped [11], fabric [12], cylindrical [13], folded-plate [14], rhombic grid multiunit [15], and etc. Each structure can be employed to extract energy from different sources and utilized in a different category of applications. However, their sizes, cost, and the working principle may differ from one another. In this study, a cantilevered based structure was employed due to its wide band characteristics [16]. In addition, the incorporated piezoelectric mechanism in this study acts as the cantilever beam, making it a hybrid system. Previous studies regarding the hybridized devices contained different characteristics and obtained dissimilar results. These devices possessed different constraints or were developed depending on the requirements of the source input.

Design characteristics and low-frequency operation of the system are the major challenges in vibration-based energy harvesting technology. To tackle this issue, various strategies have been implemented in the past in order to improvise the performance of triboelectric energy harvesters (TEHs). Dhakar [16] developed a cantilevered triboelectric harvester that increases the operational bandwidth by utilising the contact electrification process. Weiqing [17] demonstrated triple cantilevered based triboelectric nanogenerator with surface modification by incorporating nanowire arrays. Yuanjie [18] proposed a hybrid triboelectric harvester for harvesting two types of energy from water wave in a single device. In the triboelectric mechanism, geometrical factors such as the type of the material [19], surface area [20], surface morphology [21], and separation gap [22] play an important role in terms of charge generation. However, the performance of the

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piezoelectric material is dependent on its dimension, shape, mass, and stiffness of the beam. In order to overcome and compromise these factors, two separate designs namely (i) dual cantilevered hybrid triboelectric harvester and (ii) touch based hybrid triboelectric harvester were proposed in this study. The novelty of this study can be said to be the dual cantilever structured design which none of the researchers have attempted in the past. Furthermore, the effect of the surface area of triboelectric materials along with the influence of the extension beam on the output performance of harvesters was evaluated.

METHODS AND MATERIALS

The prepared harvesters had common characteristics such as similar materials, while copper was employed as the electrode and piezoelectric specimen for hybridization. However, the harvesters were different in terms of structural representation in which factors such as cost, size, and feasibility of the design were considered. Figure 1 illustrates the proposed designs namely ((a) (i) and (ii)) Dual cantilevered hybrid triboelectric harvester and ((b) (i) and (ii)) Touch based hybrid triboelectric harvester.

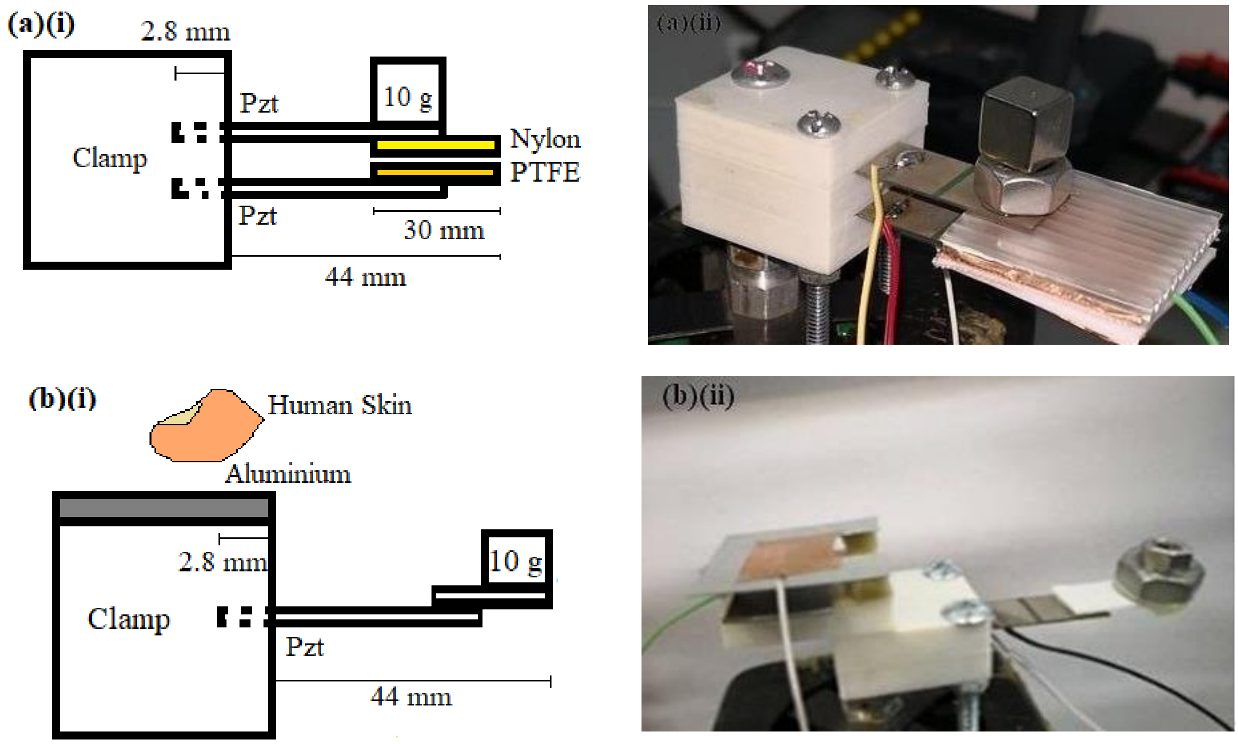


Figure 1. (a)(i) Schematic diagram, (a)(ii) Prototype of Dual cantilevered beam.hybrid triboelectric harvester and (b)(i) Schematic diagram, (b)(ii) Prototype of Touch based hybrid triboelectric harvester

The prototype displayed in Figure 1(a) contains dual piezoelectric beam and triboelectric layers, nylon and polytetrafluoroethylene (PTFE), attached at the tip of the top and bottom beams and facing each other. At an instant when the device is positioned on a shaker, the deflection of the beams brings the triboelectric layers into contact. In order to attain contact between the beams, tip mass was placed at the top beam in a way that both beams vibrate at a different phase, which will eventually increase the efficiency of the contact and separation. In addition, the dual beam configuration assists in the broadening of the frequency bandwidth resulting from the stiffening condition, as the bottom beam restricts the motion of the top beam. In contrast, design (b) was comprised of a single piezoelectric beam and triboelectric layers of aluminium located at the upper part of the clamp. Human skin touch was applied on the top of the aluminium surface at known intervals and the output was recorded. Moreover, since the design allows the beam to vibrate freely without any obstacles due to contact, an improvement was observed from the piezoelectric layer output. Table 1 displays the difference between the proposed designs.

Table 1. Differences between the two proposed designs

Dual cantilevered Hybrid Triboelectric Harvester	Comparison	Touch-based Hybrid Triboelectric Harvester
Two	Number of piezoelectric beams.	One
0.0318 x 0.127 x 0.00051 m	Dimensions of piezoelectric.	0.0318 x 0.127 x 0.00051 m
0.044 m	Overall length of beam	0.044 m
Nylon and PTFE	Triboelectric material	Human skin and Aluminum
10 g	Tip mass	10 g
0.009 m^2	The surface area of triboelectric layers	0.009 m^2

The prepared devices were positioned on a vibration shaker and the output voltage was estimated using a digital voltmeter. A range of input frequencies from 20 Hz to 100 Hz with an acceleration of 0.36 g was applied to the shaker. Besides that, tests were done for atleast three iterations in order to obtain accurate result with an error of ± 0.500 V. The parameters tested for design 1 was the effect of triboelectric surface area and the influence of the extension on the output of the triboelectric mechanism. While for design 2, the effect of touch-based triboelectric mechanism was studied in order to display the difference between the triboelectric layers used in both designs and their influence on the overall output performance of the hybrid triboelectric harvester.

RESULTS AND DISCUSSIONS

Dual Cantilevered Hybrid Triboelectric Harvester

The results presented in this study demonstrate the effect of the parameters tested on the overall productivity of the harvesters. Moreover, both harvesters were examined upon the same input conditions in order to avoid any data misinterpretation. Figure 2 illustrates the output of the mechanism of triboelectric at the different surface area of triboelectric layers on dual cantilevered hybrid triboelectric harvester. The employed surface areas in this work were 3 cm^2, 4 cm^2, and 9 cm^2.

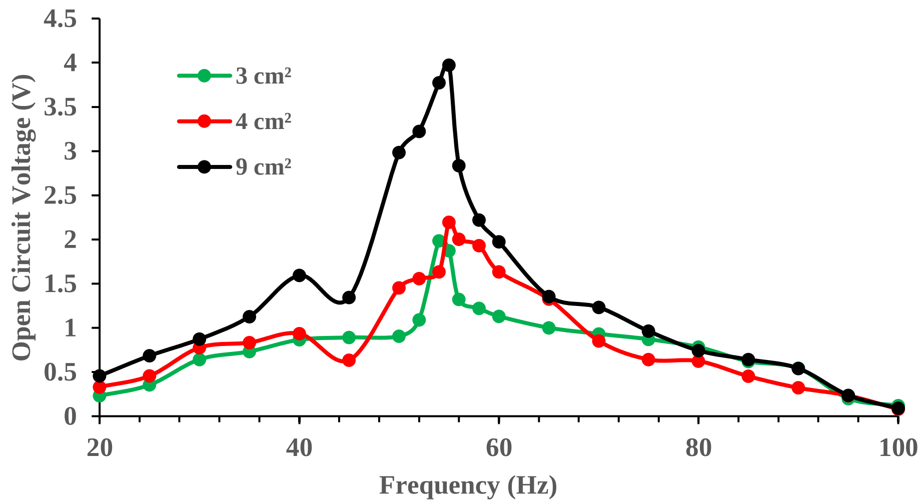


Figure 2. Open circuit voltage of triboelectric mechanism at different surface areas on dual cantilevered hybrid triboelectric harvester

The output voltage of the triboelectric mechanism displays the highest peak of 3.974 V at 55 Hz, while the lowest obtained voltage was 1.986 V at 54 Hz. In addition, it can be observed from the trend that the voltage output increases as the surface area increases. This is due to the fact that as the surface area expands the higher quantity of charge density would be accumulated on the surface. Consequently, higher rate of charge transfer occurs which results in higher value of peak output voltage. Figure 3 presents the output voltage of the open circuit of the piezoelectric and triboelectric mechanism at the surface area value of 9 cm^2 on dual cantilevered triboelectric harvester.

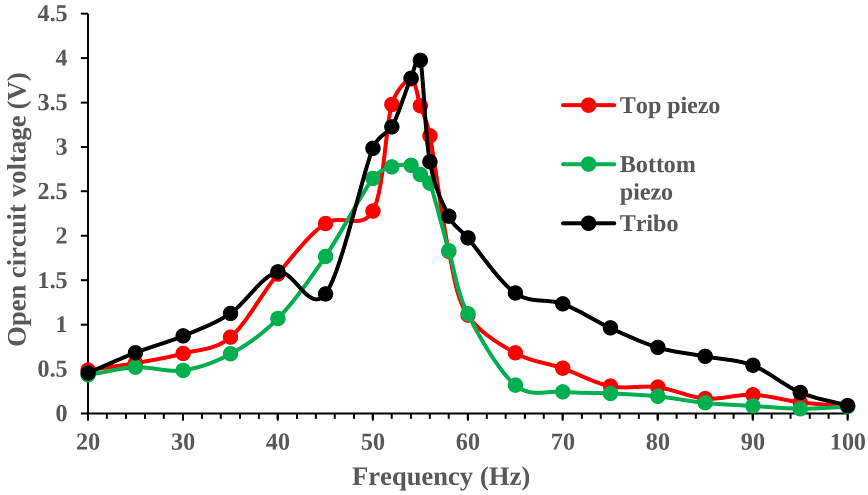


Figure 3. Output of piezoelectric and triboelectric at the surface area value of 9 cm^2 on dual cantilevered hybrid triboelectric harvester

Furthermore, figure 3 illustrates the values of output between the top and bottom piezoelectric mechanism along with triboelectric mechanism. It can be observed that the highest output was obtained by the triboelectric mechanism in comparison to the top and bottom piezoelectric beams which attained the highest voltage of 3.764 V and 2.794 V, respectively. Limited deflection of the beams and lower stress induced in the beam generated a lower voltage. On the other hand, the effect of the extension was evaluated at various extension lengths of 0 cm (without extension), 1 cm, and 2 cm. Figure 4 displays the values of the output voltage at different lengths of extension.

The highest value of output was attained when the extension length was at 2 cm, while the peak frequency was 40 Hz with an output open circuit voltage of 3.792 V. It could be observed that as the voltage increases as the extension length increases.

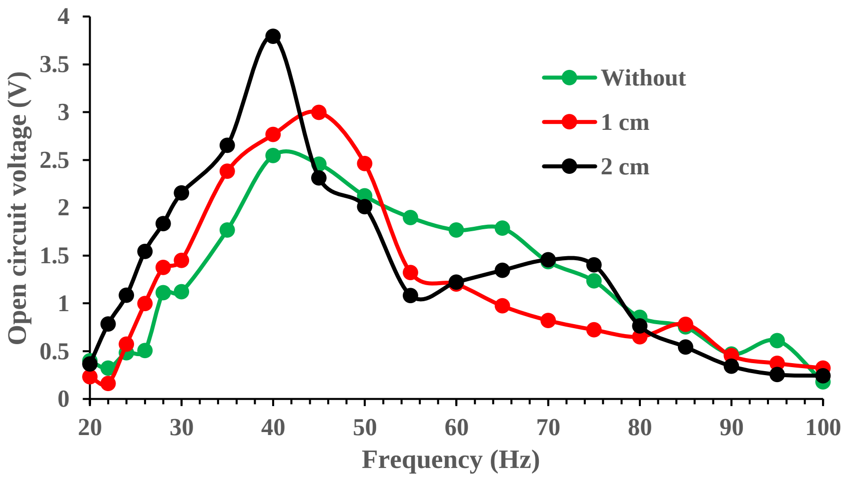


Figure 4. Output voltage of triboelectric mechanism at different lengths

This is due to the fact that as the lengths were increased, the deflection of the beam was expanded attributed to the reduced stiffness, which increases the contact force and generates higher output in comparison shorter extension lengths. Rapid contact between the layers and higher force ensures that the charge transfer is efficient. Figure 5 illustrates the overall output for extension length of 2 cm for each mechanism of the dual cantilevered hybrid triboelectric harvester.

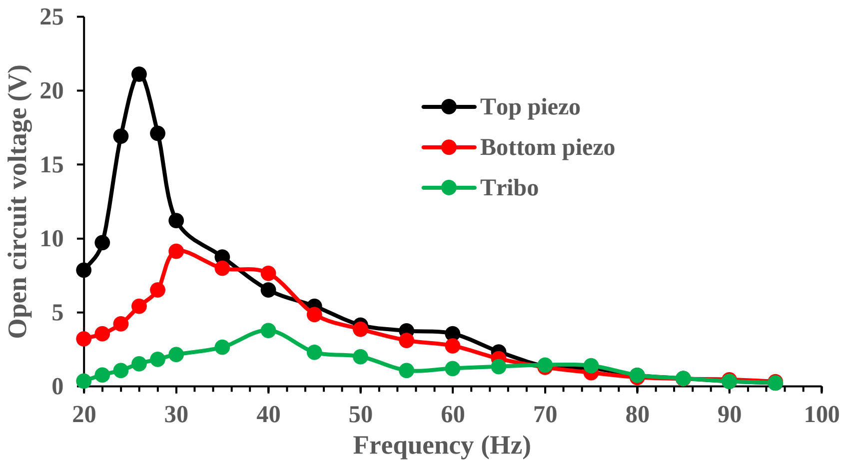


Figure 5. Open circuit voltage for piezoelectric and triboelectric at extension length of 2 cm on dual cantilevered hybrid triboelectric harvester

The graph demonstrates that the highest output attained was from the top piezoelectric beam which generated output of 21.120 V at a frequency of 26 Hz. Moreover, it was observed that a longer beam provides better deflection and higher stress which resulted in the production of higher output. Although triboelectric generally exhibits higher output voltage, in this case, the geometrical characteristic played a significant role, where the size of the device was a limitation. The complexity and compactness of the device were highly essential as the device was required to be low cost and easily applicable in various applications.

Through evaluation of the parameters on the dual cantilevered hybrid triboelectric harvester, it can be concluded that utilization of larger values of surface area and longer extension leads to the generation of the best output. Hence, they were finalized as the optimum conditions for the structure. Moreover, the device was examined across load resistors and a maximum total power output of 650 µW was obtained.

Touch-based Hybrid Triboelectric Harvester.

The optimized parameters of the surface area and extension length were used for further tests on touch-based hybrid triboelectric harvester. This harvester utilized human skin as one of the triboelectric layers. It is known that human skin is highly sensitive and was placed on top of the triboelectric series due to its capability to obtain a stronger electron affinity. Figure 6 illustrates the output of touch-based hybrid triboelectric harvester.

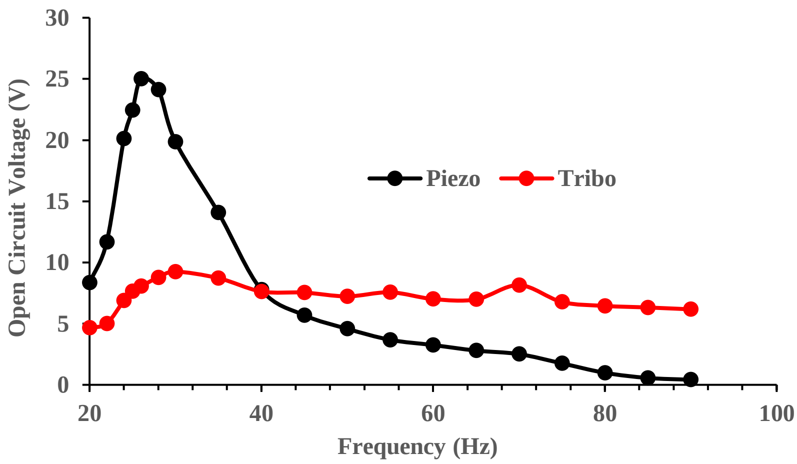


Figure 6. Open circuit voltage of piezoelectric and triboelectric of touch-based hybrid energy harvester

Human skin is highly sensitive and transmits higher content of charges on its surface in comparison to any other material. It can be observed in figure 6 that the voltage of triboelectric open circuit was 9.250 V. Moreover, the piezoelectric beam achieved a voltage of 25.01 V at 25 Hz, where the beam was free to deflect without any obstacles and an extension of the same dimension was utilized. This is as a result of higher stress induced in the beam which increases the voltage of the open circuit. The peak voltage of both designs was achieved within the input frequency range and less than 50 Hz. Touch-based hybrid triboelectric harvester generated a maximum total power of 1220 µW. Each energy transducer was tested over a load and the power output was summed up by employing the following equation;

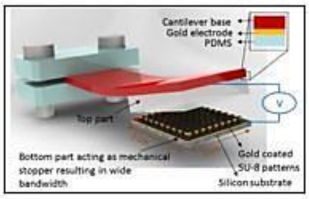
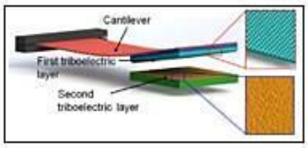
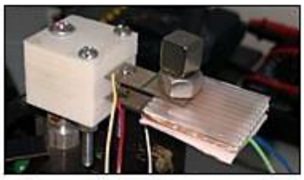
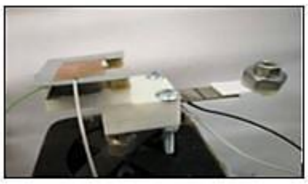
$$P_{equivalent} = P_{piezoelectric} + P_{triboelectric} \tag{1}$$

Comparison of the developed harvesters

The dual cantilevered and touch-based hybrid harvesters have similarities in terms of the transduction mechanisms present in their system. However, these harvesters performance vary due to their structural differences and materials used. The dual cantilevered hybrid harvester produced low power which could be due to limited deflection of the beams, dependency of triboelectric layers on the beam's deflection and smaller separation gap. Whereas, the touch-based hybrid harvester produced relatively high power due the independent operation of the transduction mechanisms.

A comparison of these devices with other developed devices of similar structures was performed in order to display the differences between them and enhancements of the obtained output. Table 2 demonstrates the comparison of the proposed designs with other developed devices. Each design contains several criteria and limitation, but they differ in terms of working operation. Dhakar [16] developed a cantilevered structured triboelectric mechanism with triboelectric layers at the bottom end of the beam while one of the layers performing as a stopper. In his work, the deflection of the beam allowed the contact between the layers with the stopper stiffening the beam and in return, it increased the frequency bandwidth. Furthermore, the surface modification was executed on the triboelectric layers in order to ensure enhanced contact by increasing the surface area. A peak output power of 0.18 µW was obtained across the 500 kΩ load. Moreover, an extension of his work with the same structure, Dhakar [23] studied the influence of elastic PDMS microstructures on the generated output of the device. From this study, an output power of 0.69 µW was attained where improvement was observed in comparison to his previous work. In addition, it can be concluded that surface topography plays an important role in the triboelectric mechanism.

Table 2. Comparison with other developed designs

No.	Design	Structure	Frequency (Hz)	Amplitude (g)	Load (kΩ)	Power (µW)	Ref.
1.		• Cantilevered with stopper. • Triboelectric layers PDMS and gold were used.	22.6	1.4	500	0.18	[16]
2.		• Cantilevered with stopper. • Triboelectric layers PDMS and copper used.	25	1	5800	0.69	[23]
3.		• Dual cantilevered. • Triboelectric layers Nylon and PTFE.	26	0.36	160	650	This study
4.		• Cantilevered. • Touch based • Triboelectric layers Aluminium and Human Skin.	25	0.36	400	1220	This study

This study avoided the employment of surface modification techniques for the purpose of increasing the surface area, which is an added advantage in terms of cost. Moreover, hybridizing triboelectric mechanism with piezoelectric mechanism it is known to be beneficial since the output power from each mechanism at different frequency can be extracted from various sources of vibration and is usable for a wider range of applications. It was observed that the dual cantilevered hybrid triboelectric harvester and touch-based hybrid harvester produced higher outputs in comparison to previously developed devices. Although the highest output power was obtained from a piezoelectric mechanism compared to the triboelectric mechanism, it can be stated that each mechanism compliments each other at different frequencies. Triboelectric mechanism output power in this study was lower for both designs compared to the piezoelectric mechanism, which could be attributed to the limited surface area in order to ensure the desirable size of the harvester, while no surface modification was performed on the triboelectric layers and minimal separation gap.

Moreover, in these hybrid harvesters, the piezoelectric mechanism had a higher output in comparison to the triboelectric mechanism. Future optimization on the design factors for the triboelectric mechanism may deliver desirable results for the performance of hybrid harvester devices.

CONCLUSIONS

This study evaluated the performance of hybridized triboelectric energy harvester with two different designs namely dual cantilevered hybrid triboelectric harvester and touch-based hybrid triboelectric harvester. The performance of these designs was examined with different parameters such as the effect of surface area and extension by maintaining the separation gap, acceleration, and tip mass at constant values. Moreover, it was observed that larger surface area contributes to higher performance output for the triboelectric mechanism, while longer extensions produced better output for both triboelectric and piezoelectric mechanisms.

Furthermore, the dual cantilevered hybrid triboelectric harvester was designed for the purpose of being utilized in wide range of low-frequency bandwidths. In addition, structural differences between both designs had an influence on the size and cost of fabrication of the overall device. The maximum power achieved for dual cantilevered hybrid harvester was 650 μW across a load of 160 kΩ and frequency of 26 Hz. On the other hand, touch-based energy harvester produced a peak power output of 1220 μW across a load of 400 kΩ at 25 Hz. It was observed that the piezoelectric mechanism produced higher output in comparison to the triboelectric mechanism as a result of different working principle and design factors.

Future work is required on improvising the triboelectric mechanism through studying and analyzing design principles such as surface modifications, separation gap, and contact force in order to enhance the performance of hybridized energy harvesters for low power applications.

ACKNOWLEDGMENTS

The authors would like to acknowledge Institute of Sustainable Energy, Universiti Tenaga Nasional (UNITEN) for the facilities and funding in order to conduct the research.

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