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Study of the Effect of Connection Type on Piezoelectric Energy Harvester

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A B S T R A C T

The ability to convert mechanical energy into electrical energy by piezoelectric materials makes them suitable alternatives to use in energy harvesters. So, the efficiency of a piezoelectric energy harvester is the main limitation. One of the desired approaches to increase efficiency is using a piezoelectric array in the harvester. In this paper, a numerical method has been used for the comparative study of series and parallel array behavior in different types of input force. The effect of input force type, frequency of input force, and type of array connection on energy harvester efficiency with the proposed design have been investigated. Numerical results have been verified with experiments. Results indicated that a series connection can produce 2.2 times the maximum voltage larger than a parallel connection. Also, they show that the input force shape function is the effective parameter for a piezoelectric energy harvester with an array structure. The results show a similar effect of the input force shape function on the behavior of piezoelectrics in both types of electric connections (parallel or series). In general, it can be seen that the waveform of the output voltage after applying the load with a square function was similar to its function. Also, the change in the parameters of the input force with the sinusoidal function causes a direct change in the same character of the generated voltage waveform.

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INTRODUCTION

The introduction of new technologies has provided the ability to improve and increase efficiency in many applications (1). The use of piezoelectrics is the basis of many of these technologies. Piezoelectric energy harvesters convert mechanical energy to electrical energy because of the electrostriction effect (2). This effect occurred because of the unbalanced microstructure in piezoelectric materials (3). This type of energy harvesting is suitable for different applications, from street waking energy to ship motor vibration energy harvesters (4). Each potential energy level is related to the specific type of input force.

The efficiency of piezoelectric energy harvesters is a main limitation for them. The efficiency of piezoelectric material is strictly dependent on the input frequency. The nearest input frequency to the resonance frequency of the harvester leads to increasing output voltages. Producing high-efficiency piezoelectric materials and new topological designs are ways to decrease this limitation. Using an array harvester instead of a single element is an effective alternative to reach this goal. The type of connection in the array is another key effecting factor for this solution (5). Xue et al. (6) investigated the use of several piezoelectric bimorphs with different geometry and resonant frequency in energy harvesting. They reported that the use of combined connections (parallel and series) can increase the working frequency band of the system. Zhu et al. (7) presented a finite element model to study the effect of the input force on current, voltage, wasted energy, and harvested energy obtained by piezoelectric. They pointed out that the maximum mechanical displacement does not produce the maximum electric power because this parameter is only a function of voltage and current. Liao and Sodano (8) reported that based on the proposed model, the type of piezoelectric connection (parallel or series) does not affect the

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maximum electrical power that can be produced by the set of piezoelectric. However, they explained that a series connection harvester can achieve the same output power as a parallel connection while having four times the resistance. Zhu et al. (9) studied the effect of using several piezoelectric layers on the amount of harvested power. They generally observed that using more piezoelectric layers, whether connected in parallel or series, increases the output power. It is noteworthy that they found that the use of two parallel piezoelectrics can produce more output power than three piezoelectrics with parallel connections. Lin et al. (10) examined the performance of parallel, series connections in piezoelectric energy harvesting and pointed out that the harvester with the parallel connections can produce maximum voltage with medium bandwidth, but the series connections need the maximum bandwidth to produce maximum voltage. Sun et al. (11) by evaluating the type of piezoelectric connection and studying the piezoelectric equation found that in the energy harvesting process, using piezoelectrics with 33 working modes improves the voltage and power output. Also, the harvester with a series connection can produce a higher voltage that can be used in electronic devices, but the parallel connection can record higher current and output power. Zhao et al. (12) studied the performance of one micro piezoelectric cantilever array by applying 0.2 to 1 g force. The results of this research showed that the energy loss is one-fifth in series connection compared to parallel connection. Wang et al. (13) found that the frequency and the amount of load applied to the piezoelectric have a productive effect on the increase in the harvested voltage. They mentioned a 100x100 mm device as optimal harvest energy. This setup can produce the highest output value (11.67 mW) with a load of 0.7 MPa and a frequency of 15 Hz. Khalili et al. (14) presented a model to check the amount of voltage harvested according to the power and frequency applied to the piezoelectric, which was in acceptable agreement with the experimental results. Also, they reported that a considerable range of voltage 95 V to 1190 V) can be obtained by applying force with a frequency of 66 Hz. Asano et al. (15) found that using multi-layer piezoelectric with parallel connections in the shoes and applying the force of human weight to them, were able to produce energy equal to 1.29 mW and that was enough to turn on the LED lights in the shoes. He et al. (16) investigated the effect of magnet length and piezoelectric geometry in their setup on the amount of force obtained. They found that a magnet with a length of 7 mm and a rotation speed of 550 rpm is in the optimal state and produces the maximum energy. Lallart (17) offered a refined layout for harvesters with parallel and series connections obtained with the help of a rectifier, which was able to reduce the power loss in the energy harvesting process significantly, under the desired conditions.

Although the aforementioned researchers have paid much attention to studying the effect of piezoelectric connection type (parallel or series) in the energy harvesting process and the factors affecting it, the function shape of the applied force has not been investigated as a parameter with a direct effect on the obtained energy. In this study, after validating the presented finite element model with the experimental results and ensuring its accuracy, the effect of changing the input force function on the voltage obtained from a harvester with parallel or series connections has been investigated. Results show that the applied force shape function plays an important role in the quality of energy harvesting containing the value and the duration of peak voltage. This subject was not studied before.

MATERIAL AND METHODS

Numerical simulation

The mechanical force causes a mechanical deformation in the piezoelectric, which according to the properties of the material, leads to the production of electrical voltage. Therefore, it is necessary to use the physics of mechanical and electrical simultaneously to simulate this process accurately. According to all the mentioned points, COMSOL Multiphysics software was chosen for this simulation because of its ability to coupling between different physics. In the first step, an unimorph harvester including a piezoelectric material layer and a substrate according to Figure 1(a) with a circular cross-section was modeled, and it can be used to make a harvester array like Figure 1(b). Then, the properties of each material are assigned to related parts. In other words, PZT5 is assigned to the piezoelectric part and Copper is assigned to the substrate.

In the Solid mechanical physic, the substrate was constrained in all degrees of freedom, and the load was applied perpendicularly to the piezoelectric surface. Different force function types were selected for the piezoelectric energy harvester load to study the effect of force function shapes. Determining the piezoelectric connection types in the energy harvester (containing series and parallel) was done in electrostatics physics in the COMSOL software. The schematic of the intended connection types is depicted in Figure 2. Two mentioned physics were coupled by Piezoelectric physics, and simulations were performed in a time-dependent type. The simulations were repeated for independence from mesh size, and so the size of the obtained meshes was obtained according to Table 1. Figure 3 shows the meshed

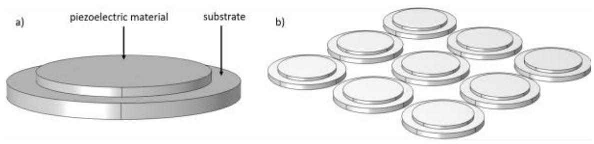


Figure 1. a) Unimorph harvester. b) 3*3 harvester unit

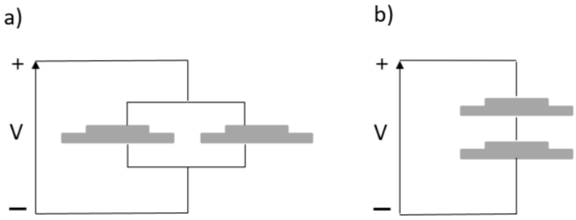


Figure 2. Harvesting unit with (a) parallel connection, and (b) series connection

Table 1. Mesh parameters

Parameter	Magnitude
Maximum element size (mm)	0.12
Minimum element size (mm)	0.03
Maximum element growth rate	1.45

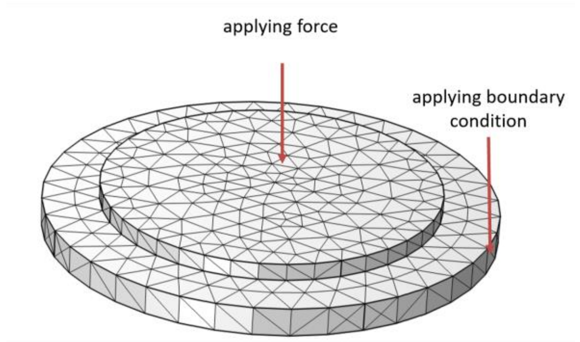


Figure 3. Meshing of a harvester

model. With mesh independence analysis and selecting the appropriate element type and size, the effect of meshing error on results can be neglected and the numerical simulation was stable and repeatable.

Experimental tests

To have an experimental validation of the presented numerical model, an experimental setup according to Figure 4 was designed and fabricated. In order to decrease uncertainty, each test was repeated at least 3 times. In this setup, 9 uni-morph piezoelectric elements were connected. Springs used in this setup not only provide continuing energy harvesting working conditions but also potentially produce changeable harvester stiffness (by substituting springs with different stiffness), and as a result the resonant frequency of the harvester can be changed. As mentioned before, this is an important point for using the presented energy harvester in different applications. Because if the force stimulation of piezoelectrics is close to the harvester resonance frequency, the efficiency of the piezoelectric energy harvester will increase. Figure 5 shows the method of connecting piezoelectrics in the setup.

The harvesting part consists of 9 piezoelectrics with an outer diameter of 50 mm. Piezoelectrics were positioned squarely (Figure 5) on a foam board, which significantly contributes to the better performance of piezoelectrics. In this part, piezoelectric can be connected in two ways: parallel and series. Considering that the applied force should always be applied in the direction perpendicular to the surfaces of the piezoelectric, a wooden structure is used to hold the weights and keep the direction of their movement in the experimental test.

RESULTS AND DISCUSSION

Validation

Before studying the process with the help of numerical simulation results, the validation of the simulation should be done based on the experimental results. Based on the results obtained in harvesting energy by parallel connection, the obtained voltage was 12 V. After applying the initial conditions according to the test, such

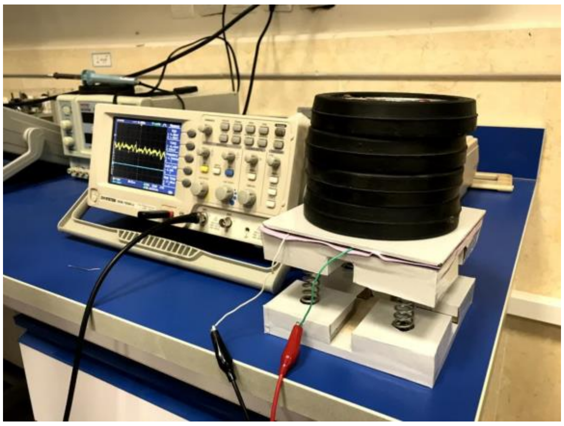


Figure 4. Experimental Setup


Figure 5. Schematic of piezoelectric in series connection

as the amount of power and the duration of its application, the voltage value according to numerical simulation was around 13 volts was recorded as the voltage produced by the software. Comparing the results shows more than 92% agreement, which confirms the validation of the simulation. Also, similar to the experimental results (Figure 9a), Figure 6 shows the same output waveform in parallel connection in simulation results, and Figure 7 illustrates the behavior of piezoelectrics after applying force.

Impact of piezoelectric connections

Based on section 1, the connection type of harvesters is an influencing parameter on the maximum amount of electricity that can be harvested by piezoelectric energy harvesters. Connection type changes the electrical and total impedance as a result and can change the frequency response of the transducer. Besides, this subject can vary the resonance behavior of the harvester.

In the experimental test results, 38.5 kg force is applied to the energy harvester with series connection, and the output voltage in this case is reported in the range of 27.5 V. In addition, the finite element model results with similar initial and boundary conditions show similar outputvoltage (29V), and also similar current waveform (Figure 8) can be obtained from the middle piezoelectric in the simulation similar to the test set (Figure 9b).

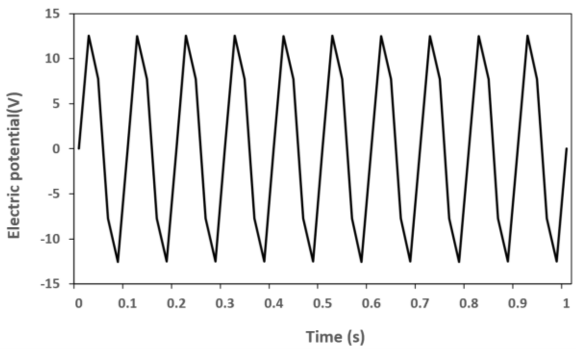


Figure 6. Output waveform in parallel connection in simulations results

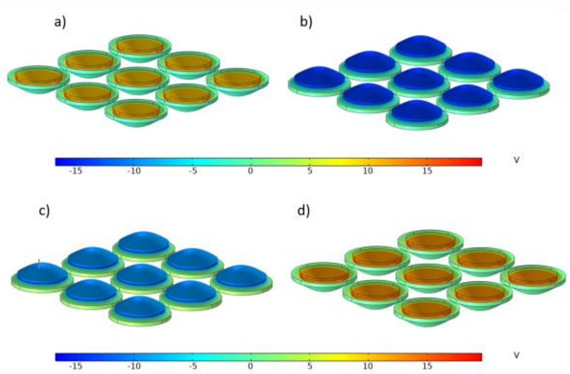


Figure 7. The behavior of the energy harvester unit under applying force from 0 to 1 second; (a)0.1 (b)0.2 (c)0.3, and (d) 0.4 seconds

Considering the experimental and numerical results and the simulation results for the collection set with parallel connection mentioned in section 4.1, it can be seen that the voltage produced when using the set with series connection is 2.2 times the voltage produced by the set with parallel connection. The waveform created by two parallel and series connections was recorded by an oscilloscope which is shown in Figure 9. It can be seen that it is significantly larger in the series connection.

Impact of the applied force magnitude

It is clear that in piezoelectric harvesting energy, increasing the mechanical force applied to the piezoelectric can increase the output voltage. In this section, with the help of a numerical study, the effect of increasing the input force on the output voltage by the harvester unit with a series or parallel connection has been investigated. The results of this investigation have been summarized in Figure 10 for parallel connection and in Figure 11 for series connection.

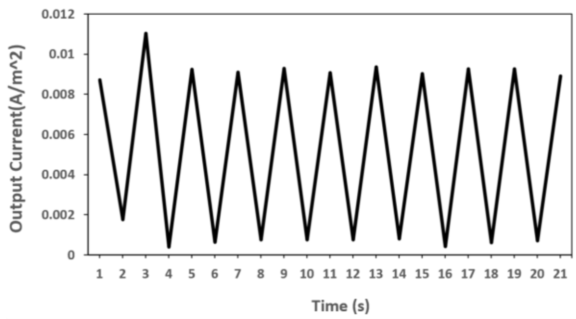


Figure 8. Output current in series connection in simulations results.

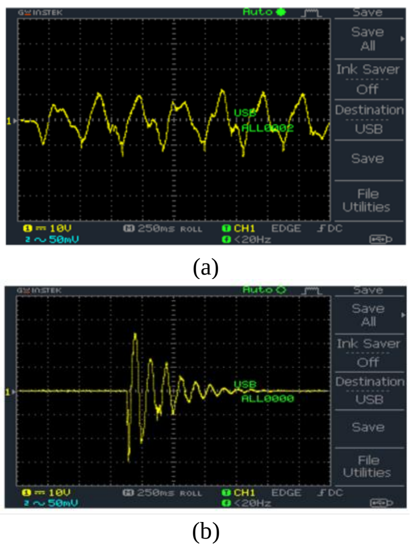


Figure 9. The waveform by (a) parallel connections, and (b) series connections

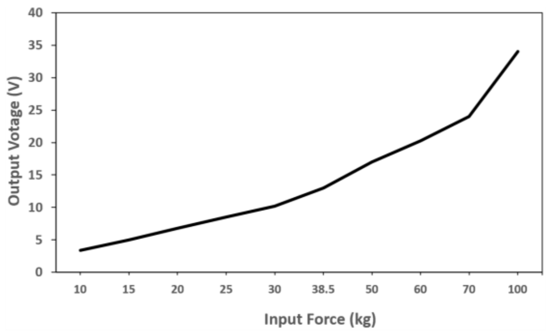


Figure 10. The output voltage of the harvester with a parallel connection

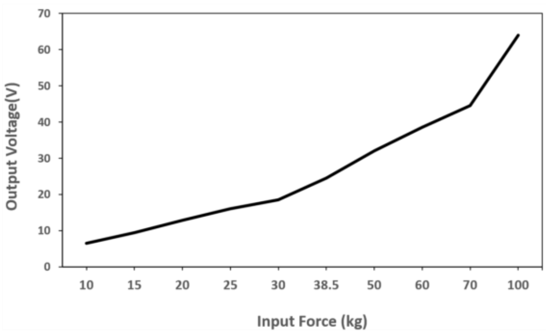


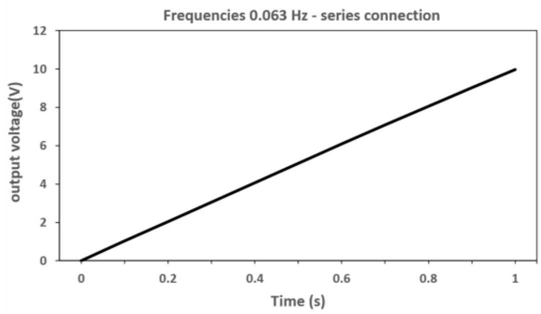
Figure 11. The output voltage of the harvester with a series connection

According to the results of Figures 10 and 11, it can be seen that due to the similar piezoelectric properties, the growth rate of the voltage compared to the input force increase was the same in both types of connection (parallel and series). Although the amount of voltage produced by the two harvesters was different.

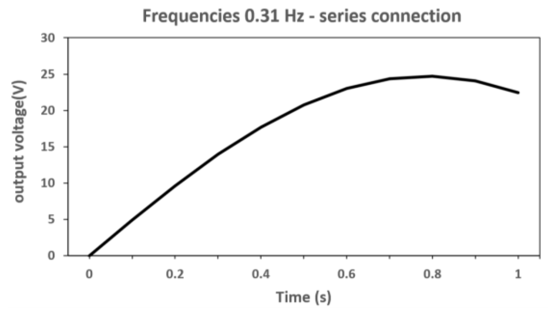
Impact of the input force type and frequency

Mechanical forces can be classified based on shape functions. In this section, the output voltage harvested from three forces with equal magnitude and the shape function of sinusoidal, square, and Impact shapes have been investigated.

The input force with a sinusoidal equation includes an amplitude and a frequency, which have an important contribution to the shape of the function. In this study, due to the constancy of the force magnitude, the amplitude of the equation is assumed constant, and only frequency determines the magnitude of the voltage harvested by the piezoelectric. Figure 12 shows the effect of the frequency of the applied force functions on the amount of voltage produced by the harvester with a series connection. It is noteworthy that the voltage generated by various frequencies has been examined during one second. According to Figure 12, excitation with frequencies of 0.031 and 0.063 Hz did not have enough time to make the



(a)



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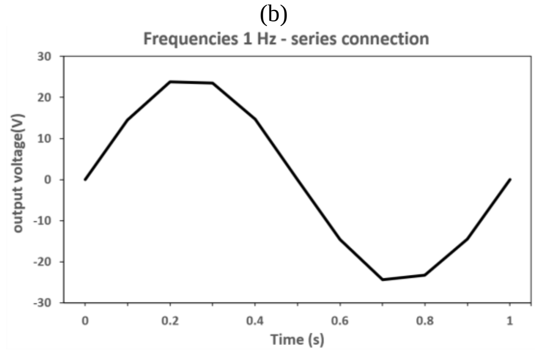

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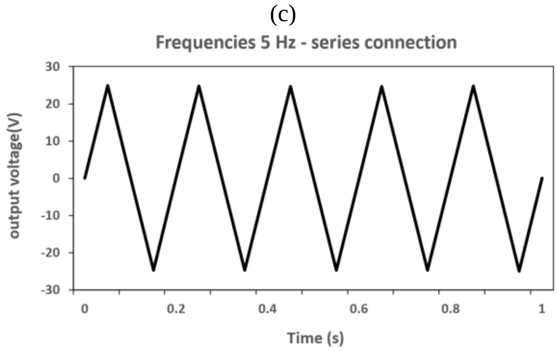
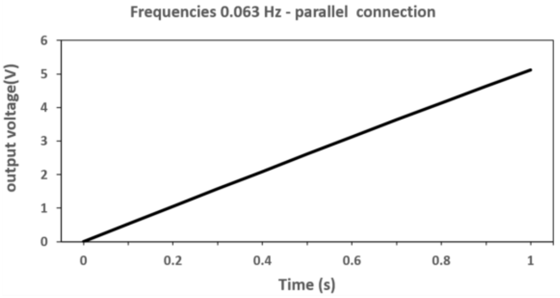


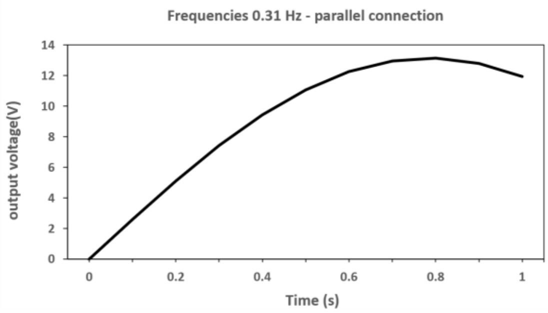
(d)

Figure 12. The voltage created in the harvester by series connection by force with frequency (a) 0.063 Hz. (b) 0.31 Hz. (c) 1 Hz. and (d) 5 Hz.

maximum voltage of piezoelectric and harvest just 2.6 and 5 V, respectively, while the frequency of 0.31 Hz was able to produce 24 V. Also, at higher frequencies, it can be seen that the maximum voltage is harvested (25 v) and The number of cycles this voltage is generated in one second grows with increasing frequency, which means more harvested electrical power in one second. Therefore, in general, the sinusoidal function can generate a higher voltage magnitude (50 V) than the step function (25 V) applied in the initial simulation, and increasing the frequency, Although far from the resonance frequency, in it causes a significant growth in voltage harvested.



(a)



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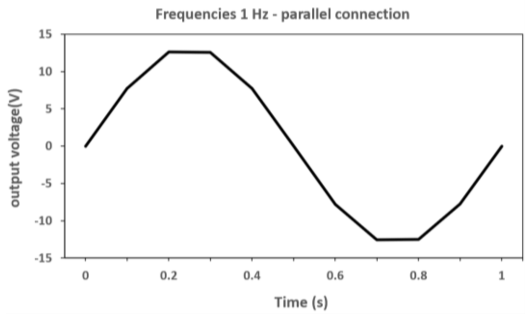

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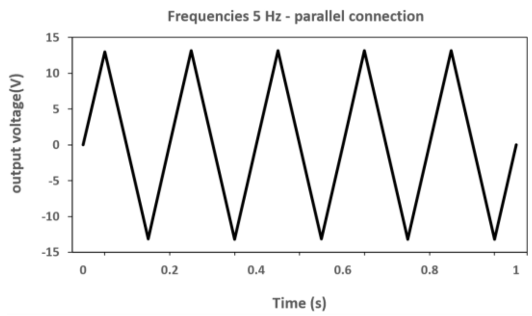
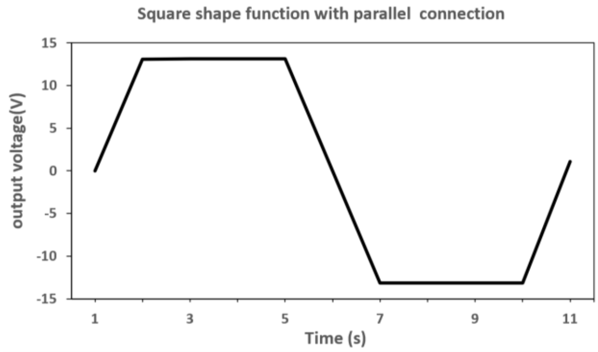


(d)

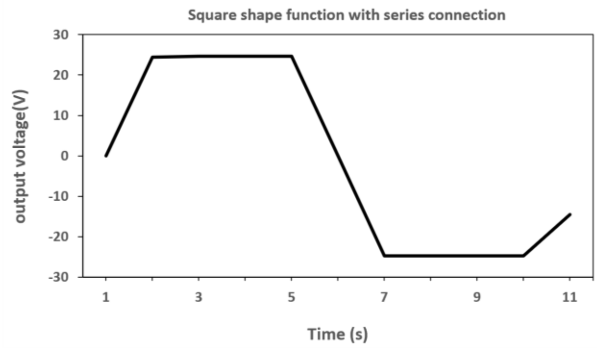
Figure 13. The voltage created in the harvester by parallel connection by force with frequency (a) 0.063 Hz. (b) 0.31 Hz. (c) 1 Hz. and (d) 5 Hz.

Figure 13 shows the same trend for the parallel connection harvester. The frequency of 0.031 Hz was only able to produce 2.6 v and the frequency of 0.063 Hz could produce 5 v. While 0.31 Hz was able to produce 13 v, higher frequencies were able to produce 24 volts, and with increasing frequency, the number of times this voltage was produced rose. For example, at a frequency of 1 Hz, this voltage is harvested only once, while at a frequency of 5 Hz, this voltage is harvested 5 times in the same period.

In general, the sinusoidal function shows the ability to produce voltage with a double value compared to the step function that was used in sections 4.1, 4.2, and 4.3. It is interesting to note that, using the input force with a square function can lead to producing a voltage with a similar shape. Using the square function achieves the same maximum voltage as the sinusoidal function, but according to Figure 14, the peak time is longer in this function, which can be useful in producing the maximum voltage for a longer time.



(a)



(b)

Figure 14. The harvested voltage by the applied force with a square shape function with connection (a) parallel, and (b) series

CONCLUSION

In this paper, the performance of uni-morph harvesters with parallel and series connections was comprehensively studied with the help of numerical simulation presented in COMSOL finite element commercial software. Numerical results were validated with experiments, and more than 90 percent accordantly was achieved. Also, the effect of the input force properties like magnitude, shape function, and frequency on harvested voltage were investigated. The maximum voltage that can be harvested with a series connection was measured as 2.2 times larger than the maximum voltage of the system with a parallel connection. In addition, increasing the applied force caused an improvement in the voltage produced in both series and parallel connections at the same ratio. Also, after measuring the force shape function, it can be reported that the sinusoidal function increases the range of the output voltage, and growth in the frequency improves the amount of received electric power. Also, the squared force function keeps the output voltage at the peak for a longer working time. The presented results can play an effective role in designing a suitable piezoelectric energy harvester for various applications. Also, due to the common logic, these results can be effective in the design of piezoelectric-based sensors. The use of research results in applications of piezoelectric energy harvest, such as wristbands and medical belts, can be the future steps of this research path.

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Persian Abstract

چکیده

توانایی تبدیل انرژی مکانیکی به انرژی الکتریکی توسط مواد پیزوالکتریک، آنها را به یک گزینه مناسب برای استفاده در برداشت کننده های انرژی تبدیل می کند. با توجه به این حقیقت که استفاده از انواع اتصال و تاثیر انواع آن (موازی یا سری) می‌تواند بهره‌وری استفاده از برداشت کننده‌های پیزوالکتریک را افزایش دهد، مطالعه آن همواره مورد توجه بوده‌است. در این مقاله از مطالعه عددی برای بررسی رفتار آرایه سری و موازی بر اساس نیروی ورودی استفاده شده‌است. تأثیر نوع نیروی ورودی، فرکانس نیرو و نوع اتصال آرایه بر راندمان برداشت کننده انرژی با طرح پیشنهادی بررسی شده‌است که نتایج آن بر اساس نتایج آزمایشات صحت سنجی شده‌است. نتایج نشان دهنده تاثییر تابع شکل نیروی ورودی بر تابع شکل ولتاژ تولید شده در هر دو اتصال موازی و سری بودند. همچنین تغییر در پارامترهای نیروی ورودی با تابع سینوسی باعث تغییر مستقیم در همان پارامتر درشکل موج ولتاژ تولیدی می شود.