

JOURNAL OF SCIENCE



SAKARYA UNIVERSITY

Sakarya University Journal of Science

ISSN 1301-4048 | e-ISSN 2147-835X | Period Bimonthly | Founded: 1997 | Publisher Sakarya University |
<http://www.saujs.sakarya.edu.tr/en/>

Title: Improving Energy Harvesting Efficiency by Vibration-Induced Stresses of Piezoelectric Patch Glued Tapered Beams

Authors: Fevzi Çakmak BOLAT

Received: 2020-02-18 11:02:10

Accepted: 2020-04-30 12:23:24

Article Type: Research Article

Volume: 24

Issue: 4

Month: August

Year: 2020

Pages: 622-629

How to cite

Fevzi Çakmak BOLAT; (2020), Improving Energy Harvesting Efficiency by Vibration-Induced Stresses of Piezoelectric Patch Glued Tapered Beams. Sakarya University

Journal of Science, 24(4), 622-629, DOI:

<https://doi.org/10.16984/saufenbilder.690571>

Access link

<http://www.saujs.sakarya.edu.tr/en/pub/issue/55932/690571>

New submission to SAUJS

<http://dergipark.org.tr/en/journal/1115/submission/step/manuscript/new>



Improving Energy Harvesting Efficiency by Vibration-Induced Stresses of Piezoelectric Patch Glued Tapered Beams

Fevzi Çakmak BOLAT^{*1}

Abstract

In this study, the effects of taper ratio and boundary conditions on the energy harvest performance of a beam element were examined. For these purpose, different taper ratio beams were analyzed numerically. The energy harvesting process was achieved by gluing a piezoelectric patch onto the cantilever tapered beam. Different taper ratio beams were designed and the effects of these taper ratio on stress change were investigated. In piezoelectric materials, when mechanical stress or strain is applied to the material, they generate electrical potential energy as a response. In order to increase the stresses on the tapered beam, the boundary condition was applied to be the thin edge of the tapered beam element in this study. In this way, the effect of tip mass was created and it was aimed to increase the stress magnitude due to vibration on the beam. Stress changes and displacement magnitudes of beams examined by applying load on beams having different taper ratio. The effect of these alterations on energy harvest efficiency was analyzed.

Keywords: tapered beam, piezoelectiric material, energy harvesting, vibration-induced stress.

1. INTRODUCTION

With the development of technology, sensor sizes are getting smaller each day. These advanced technology products require less energy. This energy need can also be provided with alternative renewable resources. In recent years [1-2], studies on small-scale energy harvesting studies are increasing. There are many studies in the literature where piezoelectric, electromagnetic or both are used together [3-8]. Voltage is generated

when force or stress is applied to a piezoelectric material. Another energy harvesting structure is electromechanical systems. Energy is harvested from these types of structures by generating voltage by moving of a structure in which the magnet and the coil interact. By giving air flow over an aerodynamic profile, vibration can be created on the energy harvesting structure. By using these vibrational movements, mechanical energy is converted into electrical energy with using smart materials. This research study is

* Corresponding Author: fcakmakbolat@gmail.com

¹ Bolu Abant İzzet Baysal University, Department of Mechanical Engineering, 14280, Bolu, Turkey
ORCID: <https://orcid.org/0000-0003-1532-7631>

investigated a novel high-performance piezoelectric wind energy harvester to improve wind energy harvesting performance with Y-shaped attachments on the bluff body. A theoretical model was developed for the analysis of the energy harvesting performance of the proposed structure. Results were experimentally examined and compared with Y-geometry and without Y geometry [9].

Another one work proposes a novel geometric structure to energy harvesting from beam based harvester to gain power in low-frequency range. A gap was created on the tapered beam and the effect of the results on the energy harvest was examined. A parametric study was carried out to ensure an equal distribution of the stress distribution on the piezoelectric patch using a package program that makes numerical solutions. By conducting experimental studies, the effect of variable geometry on energy harvesting was investigated in reference [10]. In this study, energy harvesting from piezoelectric material adhered to a beam surface with tapered geometry was investigated. The result of the study that the amount of energy obtained from the beam with tapered geometry is higher than that of a normal beam [11]. This study aimed to increase the amount of energy harvest obtained by using ambient vibrations. For this purpose, the energy harvesting performance was examined by sticking piezoelectric material on the double-sided tapered beam. The energy harvesting structure was created with three different tapered beam designs, and the results obtained with the analytical model were experimentally confirmed [12]. In this research paper, different types of non-uniform based piezoelectric energy harvesters structures are analysed its energy harvester performance. Created a rectangular cavities are introduced into the proposed harvesters to enhance the harvester voltage. The suggested harvesters are modelled analytically and are validated with experimental results [13]. This research group are investigated the possibility of using tapered beams in piezoelectric energy harvesters. Numerical simulations did not suggest any increase in the generated output power and the lack of improvement was confirmed in practice. With the help of the numerical simulations it was further

found that the tapering does work but only for certain design configurations, namely for cantilevers with long slender beams. For cantilevers with short wide beams, the tapering has no significant effect on the output power of the harvester [14]. Zang et al. analyzed of the sea wave-based energy harvesting structure. In this study energy harvesting performance was investigated using tapered beam structure glued with piezoelectric material. For this purpose, a mathematical model of the harvester is established based on Airy linear wave theory and Bessel equations to calculate the energy harvesting magnitude [15].

In this study, different types of beams examined numerically under dynamic harmonic load in order to obtain vibration-based energy harvest. In the literature, taper beam beams are used by being supported by their thick edges. In this study, in order to create a type mass effect and increase the stress value on the piezoelectric material, fixed edge boundary condition is applied different from literature. For this aim the energy harvester beam structure was fixed by the thin edge and the amount of energy harvest to be obtained from harvester structures increased.

2. DESIGN AND ANALYSIS TAPERED BEAM

Tapered beam structure is illustrated in Figure 1. Equations of motion the beam structure is given here by using Hamilton approach.

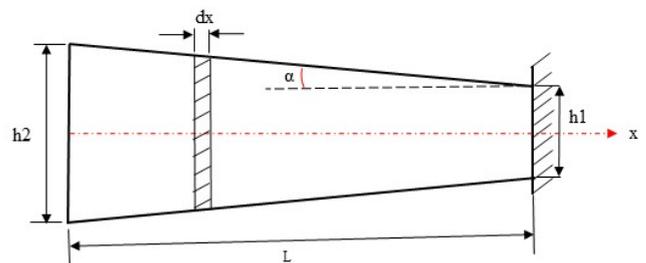


Figure 1. Tapered beam structure

$$\rho A(x) \frac{\partial^2 w(x,t)}{\partial t^2} + EI(x) \frac{\partial^2 w(x,t)}{\partial x^2} + I^2 \mu A(x) \frac{\partial^4 w(x,t)}{\partial x^4} = f(x,t) \quad (1)$$

Here $f(x,t)$ external force, μ shear modulus, $I(x)$ moment of inertia, $A(x)$ represent the area

respectively. In this study, the change of both single surface and two surface taper ratios investigated. The figure below shows three different structures to be examined within the scope of this study. Here illustrates Figure 2-a represent single surface tapered beam, Figure 2-b double surface tapered beam and Figure 2-c equivalent tip mass beam. Total mass of the equivalent tip mass beam was selected to equal the single tapered beam total mass.

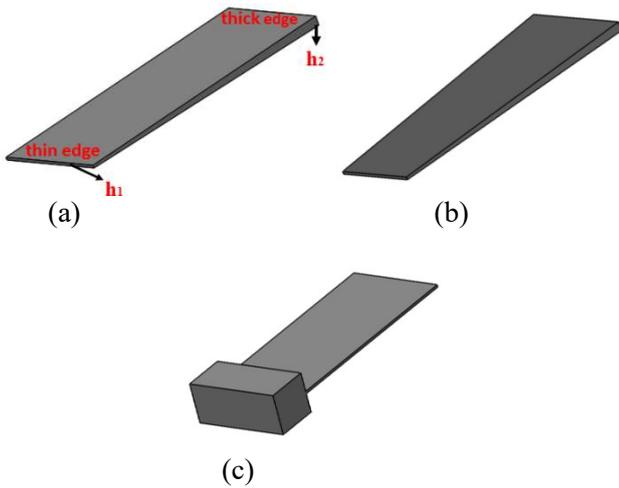


Figure 2. Taper beams a) one surface taper, b) two surface taper, c) equivalent mass beam

2.1. Nonlinear Numerical Analysis

A dynamic load is applied to the designed beam in ANSYS software to examine the under-load behavior of each proposed beam structures. As seen in Figure 3, to start the free vibration for the wing structure the dynamic harmonic load.

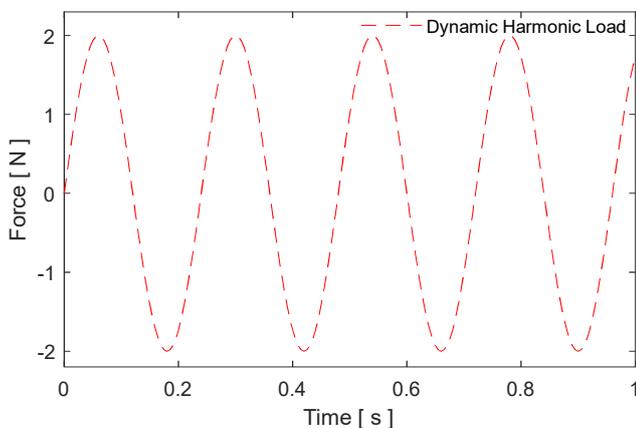


Figure 3. Dynamic harmonic load

2.2. Determining the Boundary Condition

In order to determine in which case the maximum stress occurs on the taper beam, the beam was fixed by two different boundary conditions and the results was examined. Figure 4 and Figure 5 are shows the importance of the boundary condition. The analysis results obtained show that the stress and displacement values obtained by applying the boundary condition from the thin edge are larger than the thick edge.

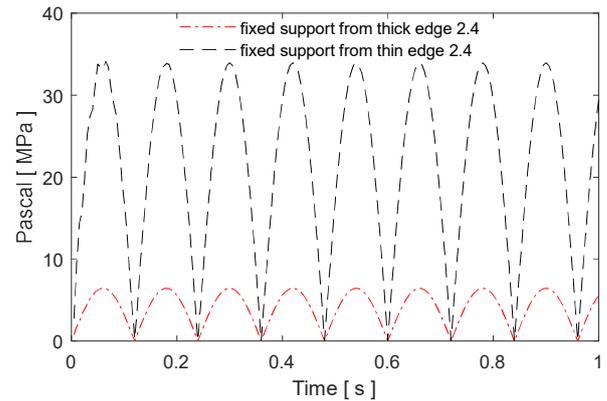


Figure 4. Stress results under the dynamic harmonic load

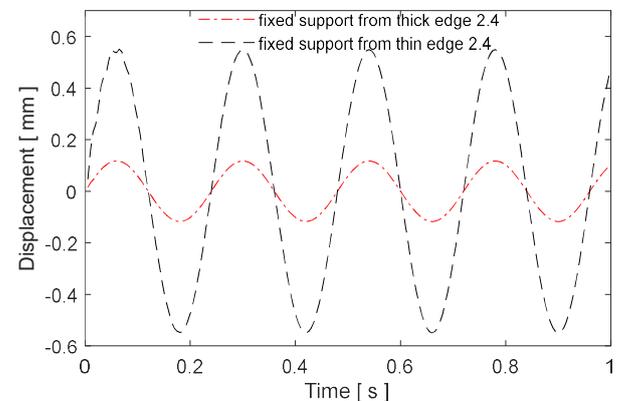


Figure 5. Deformation results under the dynamic harmonic load

2.3. Analysis for Different Types of Beam Structures

After determining the beam types of different types and thicknesses, the external force given in Figure 3 was applied to each beam structure and the effects of the results on the energy harvest were examined in detail.

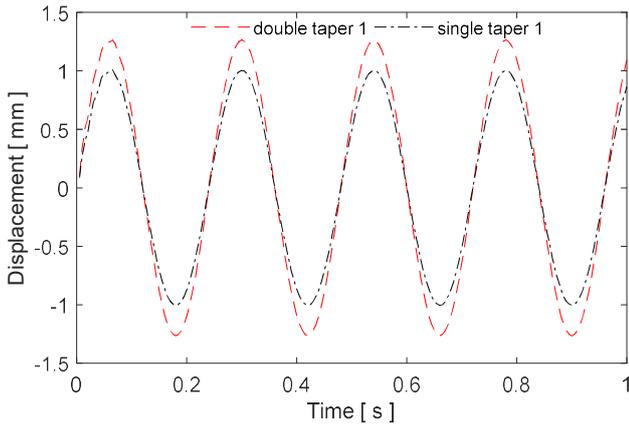


Figure.6 Single and double tapered beam displacement results

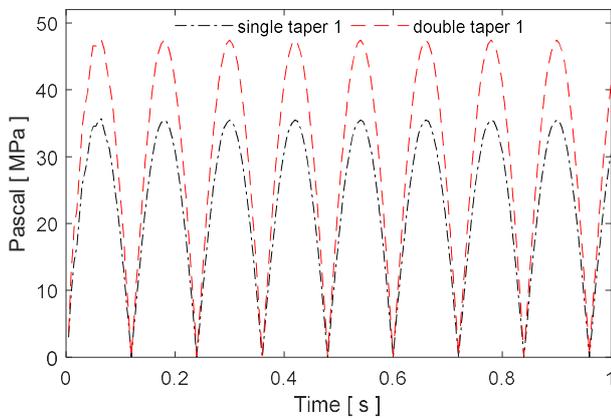


Figure.7 Single and double tapered beam stress results

Figure 6 and Figure 7 also show time-dependent displacement and stress changes of single-surface and double-surface tapered beams. The results obtained show that beside the proposed beam structure, the boundary condition is also very important on the energy harvest to be obtained.

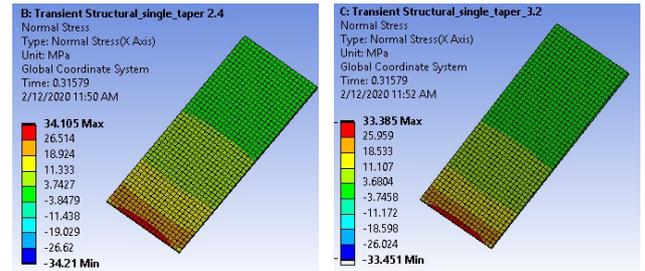


Figure 8. Tapered cases and stress changes of one surface numeric results

Table.1 One surface taper numeric result

Tapered Cases	Stress (MPa) One surface taper
$h_1=h_2=1$ mm	35.66
$h_1=1$ and $h_2=1.6$ mm	35.043
$h_1=1$ and $h_2=2.4$ mm	34.105
$h_1=1$ and $h_2=3.2$ mm	33.385

As seen in Figure 8 and Table 1, maximum stress values decrease in single surface taper beams as the rate of taper increases. The stress values formed on the beam as a result of the applied dynamic load are close to each other, but are reduced. This shows that it is not very important to increase the beam thickness to increase the amount of energy. It also shows the same results in the double-sided tapered beam as seen in the results in Figure 9 and Table 2.

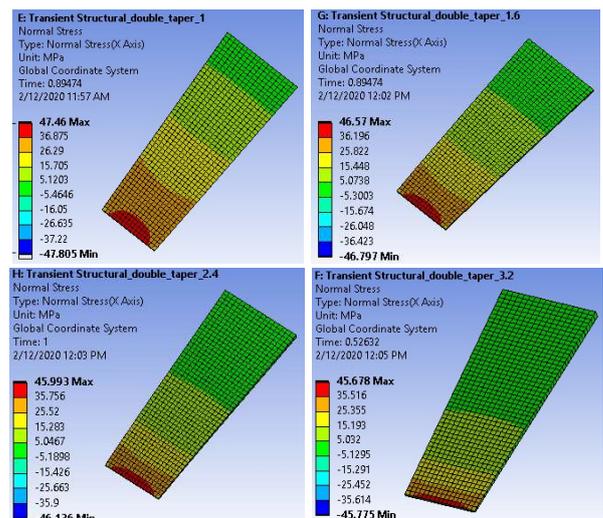
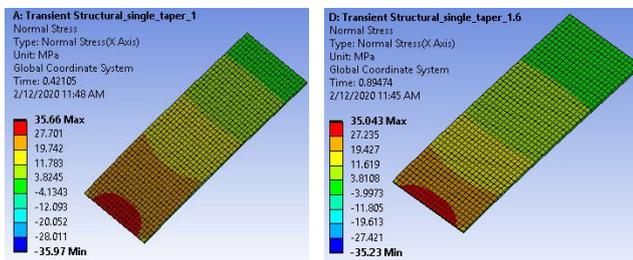


Figure 9. Tapered cases and stress changes of two surface numeric results

Table.2 Two surface taper numeric results.

Tapered cases	Stress (MPa) Two surface taper
h1=h2=1 mm	47.46
h1=1 and h2=1.6 mm	46.57
h1=1 and h2=2.4 mm	45.993
h1=1 and h2=3.2 mm	45.678

The graphics in Figure 10-13 were obtained by applying the harmonic load as illustrated in Figure 3. Here, time-dependent displacement and stress results of both single tapered beams and double-sided tapered beams were obtained for different thicknesses structures.

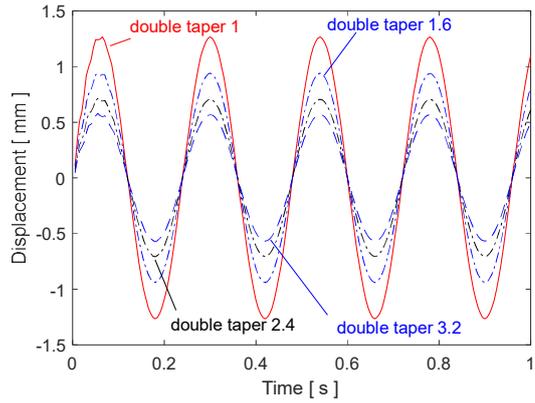


Figure 12. Different double tapered displacement results

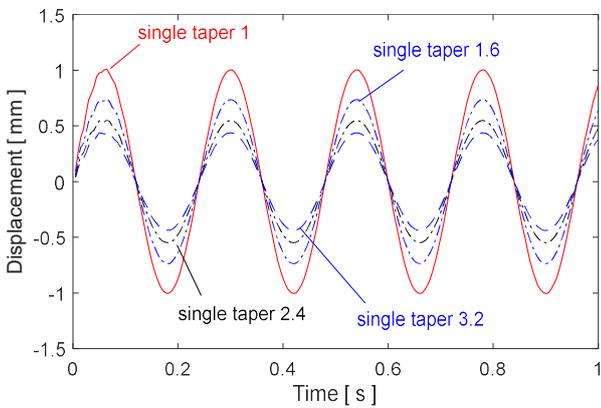


Figure 10. Different single tapered beam displacement results

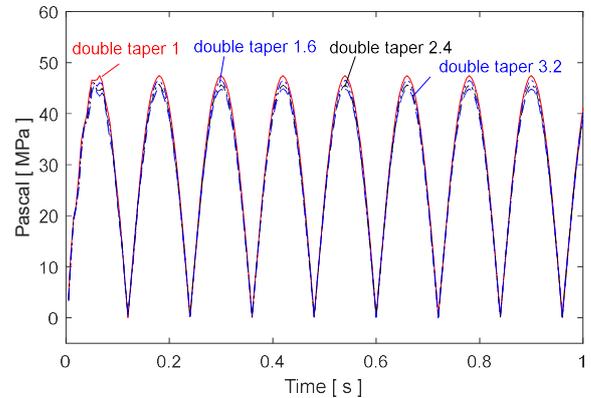


Figure 13. Different single tapered beam stress results

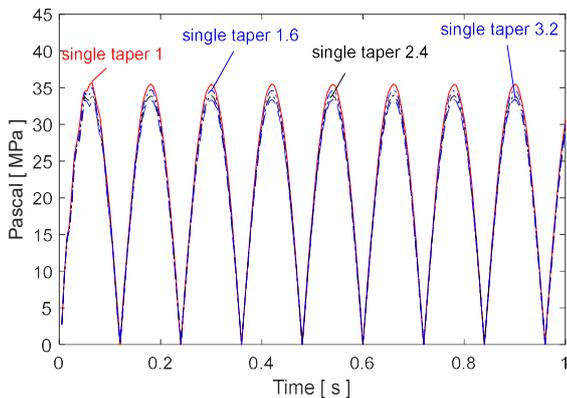


Figure 11. Different single tapered beam stress results

Numerical analysis is performed for three different beams given in Figure 2 and the results are given in Figure 14 and Figure 15. As it can be seen in the graphic results, when the external disturbance force input is the same for all configurations, the most stress and deformation occurs in the double-sided tapered beam. Apart from this, a mass is added to the end point of the beam in the same weight as the single taper beam. Numerical analysis results showed beam element with the added of end mass is have more stress and displacement than the one-sided tapered beam. The meaning of this analysis result energy amount magnitude will directly affect from structure types.

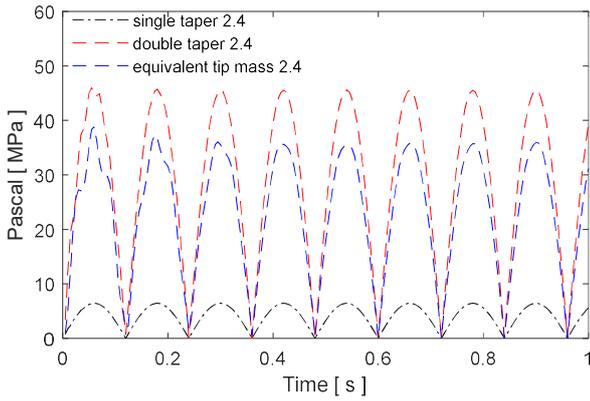


Figure 14. Different type beam stress results

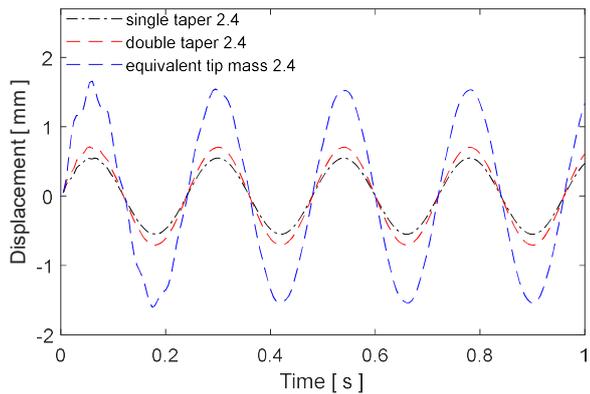


Figure 15. Different type beam displacement results

3. ENERGY HARVESTING STRUCTURES

To realize energy harvesting from piezoelectric material, it is necessary to change the shape of the piezoelectric material by giving a mechanical input. Energy harvesting from piezoelectric material can be realized against this given mechanical input. In Figure 16, a piezoelectric patch is attached to a beam element to create an energy harvesting structure. The results obtained from the previous analyzes, the beam is fixed by the thin edge to increase the amount of energy harvest. This boundary condition applied to the other selected type beams.

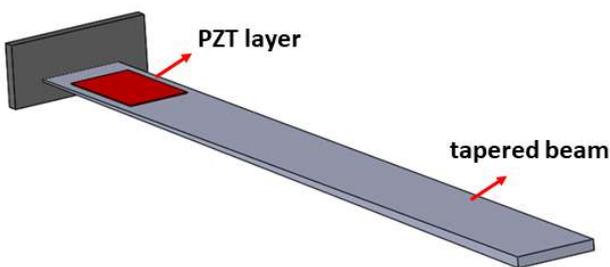


Figure 16. Energy harvester structure

Depending on the vibration of the beam element, a stress will occur on the piezoelectric patch and this mechanical energy will be converted into electrical energy.

$$\begin{bmatrix} S \\ D \end{bmatrix} = \begin{bmatrix} s^E & d^t \\ d & \varepsilon^T \end{bmatrix} \begin{bmatrix} T \\ E \end{bmatrix} \quad (2)$$

T is the stress, S^E is the strain D charge density E electric field, ε^T is the dielectric permittivity, d is the piezoelectric coefficient. For PZT, BaTiO₃, PbTiO₃ piezoelectric type materials these matrix is opened as follows [16],

$$\begin{bmatrix} D_1 \\ D_2 \\ D_3 \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 & 0 & d_{15} & 0 \\ 0 & 0 & 0 & d_{24} & 0 & 0 \\ d_{31} & d_{32} & d_{33} & 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} T_1 \\ T_2 \\ T_3 \\ T_4 \\ T_5 \\ T_6 \end{bmatrix} \quad (3)$$

$$\begin{bmatrix} \varepsilon_1 \\ \varepsilon_2 \\ \varepsilon_3 \\ \varepsilon_4 \\ \varepsilon_5 \\ \varepsilon_6 \end{bmatrix} = \begin{bmatrix} 0 & 0 & d_{31} \\ 0 & 0 & d_{31} \\ 0 & 0 & d_{33} \\ 0 & d_{15} & 0 \\ d_{15} & 0 & 0 \\ 0 & 0 & 0 \end{bmatrix} \begin{bmatrix} E_1 \\ E_2 \\ E_3 \end{bmatrix} \quad (4)$$

Converted electrical energy from a piezoelectric material calculated as follows equation [17]

$$U = QV = \frac{1}{2}(d\sigma S)(g\sigma t) = \frac{1}{2}dg\sigma^2 Volume \quad (5)$$

where surface area S and thickness t , the current constant d voltage constant g correspond to the specific co-efficients of the operational mode, σ stress, V voltage over the piezoelectric element. In order to calculate the amount of energy harvest to be obtained from this proposed structure, the stress values obtained in section 2 are substituting in the equation (4). Properties of the piezoelectric material used here is taken from manufacturer catalog $d = -123 \times 10^{-12} (C/N)$, and $g = -11.1 \times 10^{-3} Vm/N$, and total surface area $V = 50 * 30 * 0.5 = 82.5482 m^2$. Calculations were

made using these values. Stress variation is given for 3 different beams in Figure 17. As can be seen in Figure 17, the stress value obtained on the double-sided taper beam is higher than the single-surface beam. The amount of energy calculated based on these values is given in Figure 18. At the same time, it was observed that the stress value increased by adding an additional mass to the end of the beam.

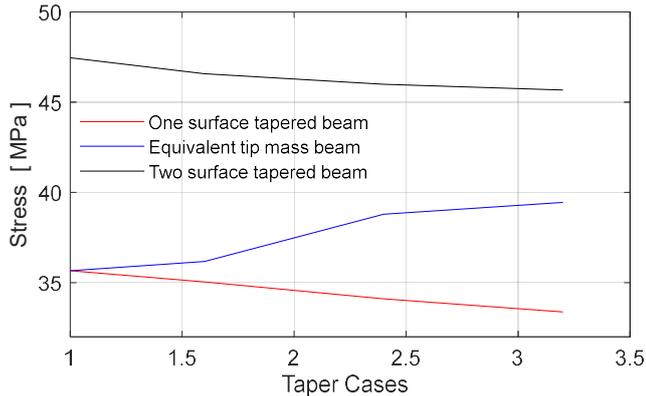


Figure 17. Stress result different beam structures

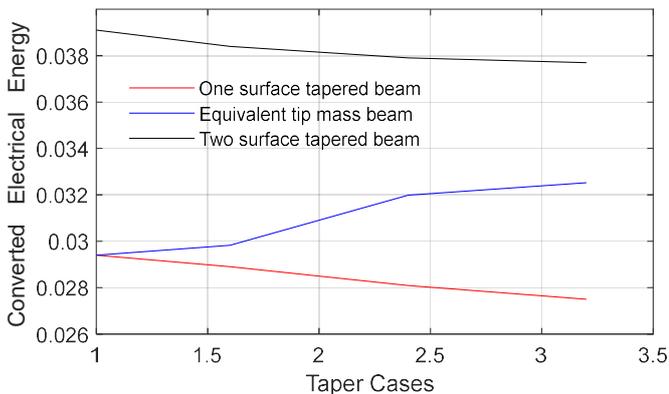


Figure 18. Converted electrical energy from different beams

4. DISCUSSION AND RESULTS

The stress value is one of the most effective factors in energy harvest from piezoelectric material. Numerical analyzes were carried out for different taper ratios, both single surface and double surface taper ratio. To increase harvest energy, in this study the boundary condition was applied to the thin edge of the beam element unlike literature. One end of the conical beam was selected as 1 mm and the other end was changed to 1.6, 2.4 and 3.2 mm, respectively. With the

numerical analysis, it was observed that when the taper was increased with one surface, the stresses on the beam increased. On the other hand, when the double surface taper is created, it has been found that these stress values increase even more. The stress change is transmitted to a directly tapered beam and piezoelectric material that is glued on the beam surface. Therefore, it has been shown that the amount of energy harvest will increase as a result of the increase in the stress value of the piezoelectric material.

Research and Publication Ethics

This paper has been prepared within the scope of international research and publication ethics.

Ethics Committee Approval

This paper does not require any ethics committee permission or special permission.

Conflict of Interests

The author declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this paper.

REFERENCES

- [1] Wang, Junlei, et al. "The state-of-the-art review on energy harvesting from flow-induced vibrations", *Applied Energy*, 267, 114902, 2020.
- [2] Zhang, Min; Hu, Guobiao; Wang, Junlei. "Bluff body with built-in piezoelectric cantilever for flow-induced energy harvesting", *International Journal of Energy Research*, 2020.
- [3] Fevzi C., Bolat, Sinan Basaran, and Selim Sivrioglu, "Piezoelectric and electromagnetic hybrid energy harvesting with low-frequency vibrations of an aerodynamic profile under the air effect" *Mechanical Systems and Signal Processing*, 133, 106246, 2019.

- [4] Fevzi C., Bolat, and Selim Sivrioglu, “Energy harvesting using an aerodynamic blade element at resonant frequency with air excitation” *Smart Structures and Systems*, 24(3), pp. 379-390, 2019.
- [5] Fevzi C., Bolat, “An Experimental Analysis and Parametric Simulation of Vibration-Based Piezo-Aeroelastic Energy Harvesting Using an Aerodynamic Wing Profile” *Arabian Journal for Science and Engineering*, 1-8, 2020.
- [6] Javed, U. Abdelkefi, A. Akhtar, I, “An improved stability characterization for aeroelastic energy harvesting applications. Commun”, *Nonlinear Sci. Numer. Simul.*, 36, pp. 252–265, 2016
- [7] Erturk, A. Vieira, W.G.R. De Marqui Jr., C. Inman, D.J., “On the energy harvesting potential of piezoaeroelastic systems”, *Appl. Phys. Lett.*, 96(18), 184103, 2010.
- [8] Bibo, A. Daqaq, M.F., “Energy harvesting under combined aerodynamic and base excitations”, *J. Sound Vib.*, 332(20), pp. 5086–5102, 2013.
- [9] Wang, Junlei, et al., “High-performance piezoelectric wind energy harvester with Y-shaped attachments”, *Energy conversion and management*, 181, pp. 645-652, 2019.
- [10] Raju, S. Srinivasulu, et al., “An effective energy harvesting in low frequency using a piezo-patch cantilever beam with tapered rectangular cavities”, *Sensors and Actuators A: Physical*, 297, 111522, 2019.
- [11] Xie, X. D., A. Carpinteri, and Q. Wang, “A theoretical model for a piezoelectric energy harvester with a tapered shape”, *Engineering Structures*, 144, pp. 19-25, 2017.
- [12] Raju, S. Srinivasulu, M. Umopathy, and G. Uma, “High-output piezoelectric energy harvester using tapered beam with cavity” *Journal of Intelligent Material Systems and Structures*, 29(5), pp. 800-815, 2018.
- [13] Raju, S. Srinivasulu, M. Umopathy, and G. Uma, “Design and analysis of high output piezoelectric energy harvester using non uniform beam”, *Mechanics of Advanced Materials and Structures*, 1-10, 2018.
- [14] Matova, S. P., et al., “Effect of length/width ratio of tapered beams on the performance of piezoelectric energy harvesters”, *Smart Materials and Structures*, 22(7), 075015, 2013.
- [15] Zhang, Jinfeng, et al., “A study on a near-shore cantilevered sea wave energy harvester with a variable cross section”, *Energy Science & Engineering*, 7(6), pp. 3174-3185, 2019.
- [16] Elvin, Niell, and Alper Erturk, eds. *Advances in energy harvesting methods*. Springer Science & Business Media, 2013.
- [17] Yang, Zhengbao, et al., “High-performance piezoelectric energy harvesters and their applications”, *Joule*, 2(4), pp. 642-697, 2018.