



## Piezoelectric energy harvesters in bridge structures: Evaluation of optimal placement and energy harvesting

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Piezoelectric energy harvesting  
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### Abstract

In the present study, energy is harvested from vibrations in bridge structures caused by vehicle passages using piezoelectric energy harvesters (PEHs). In order to maximize the energy harvested, it was aimed to specify the optimal locations of PEHs. In the study, energy harvesting from vibrations in bridge structures was achieved using three different vehicle loads and three different piezoelectric materials. The project of the Kuşsarayı-2 bridge, located in Kuşsarayı village in Baskil, Elazığ, was modelled in the ANSYS program using real measurements. The bridge was analyzed for modal, harmonic, and piezoelectric energy harvesting, respectively. The type with the highest energy production was determined using three different piezoelectric materials (PZT-4, PZT-5A, and PZT-8) for a total of 9 PEHs, and a total of 13 different analyses were performed under three different vehicle loads (60 kN, 90 kN, and 120 kN) to compare the results. The maximum total power obtained from all nine PEHs was 1.484  $\mu$ W under the 120 kN load with PZT-5A. The maximum power obtained from a single PEH (PEH-1) was 0.49  $\mu$ W. This power achieved will be adequate for wireless sensor systems used for monitoring the structural health of bridges, and considering that energy harvesting through vibration is independent of meteorological elements, unlike energy sources such as solar and wind, the environmental damage caused by waste batteries in existing systems will be prevented with the dissemination of these systems. With the development of these systems, the energy needs of services such as lighting and traffic signs can be supplied. The results provide an important foundation for the development of vibration-based energy harvesting systems in bridge structures. Thus, the study stands out as an innovative step toward sustainable energy generation in structural engineering.

## 1. Introduction

With the increasing global need for transportation, there has been a significant increase in the number of bridges. However, bridges are exposed to various disruptive factors such as earthquakes, corrosion, wind, and snowfall. Therefore, wireless sensor systems are used to ensure the safety of bridges, urgently detect structural problems, and monitor these problems [1–6]. Compared to cabled sensor systems, wireless sensor systems attract more interest due to their flexibility, easy application, cabling costs, and the potential to be placed in locations that could not be accessed previously [7, 8]. Sensors play an important role in continuously monitoring by detecting and locating damage or deterioration in structures [9, 10]. The placement of the

sensors is very important in determining the structural damage and location of the damage in bridge structures [11]. In the case that the energy needs of wireless sensors in bridge structures are met using batteries, it is necessary to change these batteries periodically as they are finite sources of energy; however, this process is highly difficult, dangerous, and costly [12, 13]. The energy needs of wireless sensors can be met by obtaining electrical energy from the vibrations caused by vehicle movements on bridge structures. The piezoelectric, electromagnetic, and electrostatic effects are different methods of harvesting energy from vibration, and, among those methods, the piezoelectric-based vibration method is more effective due to its ease of use and high-power production [14, 15]. Piezoelectric energy harvesters are one

of the most powerful sources used in wireless sensor networks, as they efficiently convert mechanical vibrational energy into electrical energy Arani et al. 2021 [16], Kim et al. 2018 [17]. Erturk [15] formulated vibration-based energy harvesting using piezoelectric transduction and modelled a cantilevered bimorph PEH to be used at a random location of a bridge. Using the finite element model, Bendine et al. [18] showed that the amounts of energy harvesting obtained from a bridge exposed to moving loads are significantly dependent on variables such as PEH locations, load speed, and load frequency. In previous studies, it was observed that PEHs were the most suitable solution for converting vibrations into useful electrical energy [19]. Peigney and Siegert [20] obtained energy from vibrations resulting from the passage of vehicles in a prestressed concrete highway bridge using PEHs. Zhang et al. [21] formulated a piezoelectric energy harvesting problem from a simply supported beam subjected to a moving harmonic load, and it was determined that PEHs should be set up at locations where vibration mode shapes are at maximum values. Y. Zhang et al. [22] modelled four different bridges on the ANSYS program and conducted a parametric study to examine the impact of PEH locations, the number of vehicles, vehicle speed, and road conditions on energy production, reporting that the amount of energy harvesting was higher under the worst road conditions, optimal vehicle speeds, and optimal PEH locations. The use of electrical energy harvested from mechanical vibrations in structures using piezoelectric materials has been a subject of interest [23]. Cahill et al. [24] formed a finite element model and performed energy harvesting from a bridge structure with train passage using PEH, stating that the amount of energy obtained was sufficient to meet the energy needs of wireless sensors used to monitor the health of structures. In addition to meeting the energy needs of wireless sensors, it is foreseen that PEHs can also be used for traffic signs, electrical signs, lighting, etc. [25]. Recent studies have optimized piezoelectric energy harvesters (PEHs) for bridge and infrastructure applications through both field experiments and finite element simulations [26–30], showing advances in design tuning, placement optimization, hybrid system integration, and real-world validation.

In the present study, the dimensions and features of a bridge in Elaziğ were modelled using the ANSYS package program to harvest energy from the bridge using piezoelectric energy harvesters. In line with this purpose, a modal analysis was performed for the bridge in a no-load condition, and suitable natural frequency ranges were calculated. Afterwards, the points where deformation is at maximum values in the bridge were detected using Harmonic analysis, and PEHs were placed in these locations. The amounts of energy obtained from the PEHs in these placement points with three different vehicle loads were calculated. The most suitable types of piezoelectric material (PZT, Lead Zirconate Titanate) were investigated, and the accuracy of the present study was compared with the literature. Different from other

studies, the optimal PEH locations in a real bridge were detected, and, in this way, maximum energy harvesting was achieved from the harvesters.

## 2. Material and method

In the present study, modal analysis was performed to determine the natural frequencies and operating frequency range of the bridge, whereas harmonic analysis was performed to detect the points of maximum deformation, and piezoelectric analysis was performed to obtain energy from the PEHs placed in optimal locations. These analyses are listed below.

### 2.1. Modal analysis

All structures have natural frequencies, which are generally the most important features of the structure. They provide insight as to how the design will react to different dynamic loads. Since the vibration characteristics of structures determine how they will react to different dynamic loads, modal analysis is performed before other dynamic analyses are carried out [31].

Free vibration occurs when the system oscillates under the impact of the forces present in the system itself in the absence of external forces and as a result of initial deviation. At one or more natural frequencies resulting from the system's dynamic features of stiffness and mass distribution, the system will vibrate [32]. Modal analysis is a linear dynamic analysis. The equation of motion involving acceleration, velocity, and displacement used in finite element analyses to determine the dynamic reaction of a structure is as follows [33]:

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{F_y\} \quad (1)$$

where,  $[M]$  represents the mass matrix while  $[C]$  is the damping matrix and  $[K]$  is the stiffness matrix. All three matrices are constant in linear dynamics and  $\{\ddot{u}\}$  is the acceleration vector,  $\{\dot{u}\}$  is the velocity vector,  $\{u\}$  is the displacement vector and  $\{F_y\}$  is the load vector. These vectors change as a function of time.

The damping rate in most structures is significantly lower than 10%, which means that the vibrations in the system are damped slowly; therefore, it is not necessary to include damping in the modal analysis solution. The term "damping" was neglected in Eq. (2).

$$[M]\{\ddot{u}\} + [K]\{u\} = \{F_y\} \quad (2)$$

By assuming harmonic solutions for the displacement and rearranging the undamped free vibration equation, the system can be reduced to a simplified form that leads to the eigenvalue problem, as given in Eq. (3).

$$[M]\{\ddot{u}\} + [K]\{u\} = \{0\} \quad (3)$$

The solution of this equation leads to the determination of natural frequencies and corresponding mode shapes of the structure.

Where  $\{U\}$  is a constant vector and  $e^{i\omega t}$  representing the harmonic time response. Here,  $\omega$  is the natural circular frequency. Substituting the harmonic solution into the governing equation leads to Eq. (4).

$$-\omega^2[M]\{U\}e^{i\omega t} + [K]\{U\}e^{i\omega t} = \{0\} \quad (4)$$

By simplifying Eq. (4), the classical eigenvalue problem is obtained.

where  $\omega^2$  represents the eigenvalue and  $\{U\}$  represents the eigenvector.

Modal parameters are widely used in bridge damage detection and design optimization [34]. In order to determine the dynamic behavior of the Kuşsarayı-2 bridge, a finite element model was created using the Modal Analysis application and the actual dimensions and material features of the bridge in the ANSYS program. Afterwards, the analysis was performed by assigning fixed support boundary conditions at the start and end points of the bridge and its piers.

## 2.2. Harmonic analysis

There are sinusoidal loads in most structures. For example, the traffic flow consisting of the vehicle load on a bridge creates a sinusoidal load on the bridge, and the bridge is forced to vibrate as a reaction to the load. Therefore, these vibrations are taken into consideration when designing bridges, and harmonic analysis is performed in order for these not to affect the health of the structure. In the finite element method, Harmonic Analysis is performed to calculate the steady state reaction of the structure due to the sinusoidal loads applied at a certain frequency. If the sinusoidal load exerted by vehicles on the bridge is repeated sinusoidally at a frequency that matches the natural frequencies of the bridge's mode shape, the vibration of the bridge is maximized and can cause severe damage to the bridge. This behavior is called resonance. In addition to vehicle load, strong wind load can also be one of the sources of vibration in a bridge structure. Additionally, harmonic analysis results allow engineers to effectively understand the importance of different model designs [35].

In the case that load is not exerted, modal analysis calculates natural frequencies and mode shapes. It does not take the reaction of the structure into consideration. On the other hand, harmonic analysis calculates the reaction of a structure under harmonic loads. This is a very significant distinction between modal analysis and harmonic analysis [36].

If the system is exposed to sinusoidal input or excitation when at a steady state, the output is also sinusoidal with the changing amplitude and phase angle, which is a significant feature of harmonic analysis. The harmonic excitation can be expressed as given in Eq. (5).

$$F_h = F_i \sin(\Omega_i t + \theta_i) \quad (5)$$

The steady-state response of the system can be expressed in complex form as given in Eq. (6).

$$u = Ae^{i\Omega t} \quad (6)$$

Substituting the harmonic displacement into the governing equation yields the harmonic form of the equation of motion, as given in Eq. (7).

$$[M]\{\ddot{u}\} + [C]\{\dot{u}\} + [K]\{u\} = \{F\} \quad (7)$$

Using the superposition principle, the system can be expressed in modal form as given in Eq. (8).

$$(-\Omega^2 + i2w_j\Omega\zeta_j + w_j^2)j_{jc} = f_{jc} \quad (8)$$

where  $\varphi$  force phase change,  $\emptyset$  displacement phase change,  $\Omega$  circular frequency applied,  $\omega$  natural circular frequency,  $\zeta$  damping rate,  $\{u_1\}$  real displacement vector,  $\{u_2\}$  imaginary displacement vector,  $\{F_1\}$  real force vector,  $\{F_2\}$  imaginary force vector,  $y_{jc}$  complex modal coordinates, and  $f_{jc}$  complex modal force.

Since fatigue damage and lifespan predictions can be made using these results that can be repeated at known frequencies, it is important to understand harmonic (sinusoidal) stress levels. On the ANSYS program, the frequency value interval of the Kuşsarayı-2 Bridge for the harmonic analysis application was set as 0-10 Hz due to the results obtained in the modal analysis. To perform the harmonic analysis application, fixed support boundary conditions were assigned under the start and end points of the Kuşsarayı-2 bridge and its piers, and a harmonic load was applied to the upper part of the bridge with vehicle passage. For the load applied, first, four car loads were considered. The mass of an average car was assumed as 1500 kg, and the total mass of four cars was multiplied by the gravitational acceleration in order to calculate the force applied to the bridge, and calculated as approximately 60 kN. Afterwards, in order to compare the results, the number of cars on the bridge was considered as six and eight, harmonic analysis was performed for loads of 90 kN and 120 kN, and the optimal PEH locations were calculated.

## 2.3. Piezoelectric analysis

The piezoelectric analysis application was performed by taking static and dynamic (transient, modal, and harmonic) states into consideration. Static analyses can be characterized within the framework of piezoelectric materials, structural elasticity, piezoelectric connection, and dielectric permittivity. For dynamic analyses, additional data such as density, structural damping, and dielectric damping are needed. When mechanical stress is applied to a piezoelectric material, an electrical load is produced, which is called the direct effect, and mechanical energy is converted into electrical energy. When electrical voltage is applied to a piezoelectric material, mechanical vibration is obtained, which is called the inverse piezoelectric effect, and electrical energy is converted into mechanical energy.

In piezoelectric analysis, structural and semi-electrostatic fields are combined through piezoelectric constants  $[e]$  as shown in Eqs. (9) and (10).

$$\{T\} = [c]\{S\} - [e]\{E\} \quad (9)$$

$$\{D\} = [e]^T\{S\} + [\varepsilon]\{E\} \quad (10)$$

where,  $\{T\}$  stress vector,  $\{S\}$  elastic strain vector,  $[c]$  elastic stiffness,  $[e]$  piezoelectric matrix,  $\{D\}$  electric flux density,  $\{E\}$  electric field intensity, and  $[\varepsilon]$  dielectric permittivity

As shown in Fig. 1, a Bimorph PEH consisting of two piezoelectric layers was designed on the ANSYS package program to be mounted under the beams on the Kuşsarayı-2 bridge with the aim of producing energy from piezoelectricity. The piezoelectric layers were connected with a resistance of 108 ohms. Based on the results obtained in the harmonic analysis, it was determined that maximum deformation occurred in the middle section of the bridge. In order to achieve maximum power, 9 PEHs were placed at the mid-point of the bridge with maximum deformation in the form of a parallel row with one PEH under each beam. To carry out the piezoelectric analysis, fixed support boundary

conditions were assigned under the start and end points of the bridge, and its piers, and a harmonic load was applied to the upper part of the bridge with vehicle passage. Additionally, in the present study, analyses were performed using various piezoelectric materials (PZT-4, PZT-5A, and PZT-8) and various numbers of vehicles (4, 6, and 8). Table 1 shows the features of the PEH, while Table 2 shows the features of the piezoelectric materials [14, 38]. Since different piezoelectric materials were used and various loads were applied, 9 different piezoelectric analyses were performed.

Table 1. Features of the piezoelectric energy harvesters [14]

Parameters	Units	Value
Length of the PZT	m	0.1
Width of the PZT	m	0.02
Thickness of the PZT	m	0.0004
Thickness of the substrate	m	0.0005
Young's modulus of the substrate	GPa	100
Mass density of the substrate	kg/m <sup>3</sup>	7165
Resistive load	Ohm	1×10 <sup>8</sup>

Table 2. Features of the piezoelectric materials [38]

Coefficient	Units	Symbol	PZT-4	PZT-5A	PZT-8
Elastic coefficient	GPa	C <sub>11</sub>	139.0	121.0	149.0
		C <sub>33</sub>	115.0	111.0	132.0
		C <sub>44</sub>	25.6	21.1	31.3
		C <sub>66</sub>	30.6	22.6	34.0
		C <sub>12</sub>	77.8	75.4	81.1
		C <sub>13</sub>	74.3	75.2	81.1
Piezoelectric coefficient	C/m <sup>2</sup>	e <sub>31</sub>	-5.2	-5.4	-4.1
		e <sub>33</sub>	15.1	15.8	14.0
		e <sub>15</sub>	12.7	12.3	10.3
Dielectric constant	nF/m	ε <sub>11</sub>	6.463	8.107	7.968
		ε <sub>33</sub>	5.622	7.346	5.312
Mass density	kg/m <sup>3</sup>	ρ	7500	7750	7600
Permittivity constant	pF/m	ε <sub>0</sub>	8.854	8.854	8.854

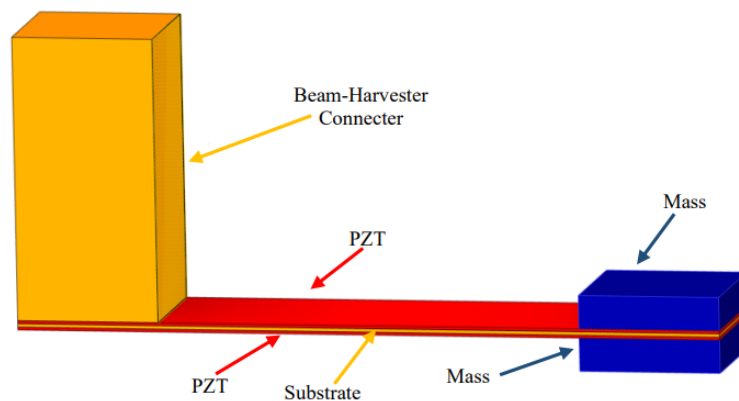


Fig. 1. Piezoelectric Energy Harvester (PEH)

### 3. Results and discussion

All physical structures have natural frequencies. When force is applied at the natural frequency of the object, it resonates, and a higher amplitude vibration response occurs. In the modal analysis application of the bridge, the first six natural frequencies are 3.7986, 4.0264, 5.0909, 5.3150, 8.3372, and 9.7049 Hz, respectively. Based on these values, the deformations on the bridge in resonance states at natural frequencies are shown in Fig. 2. Fig. 2a shows the total deformation image obtained with the lowest natural frequency value (3.7986 Hz). Maximum total deformation corresponds to the middle sections of the bridge, as 0.0011662 m. In the piers of the bridge, the total deformation was calculated as zero due to the presence of the lowest vibration. Through natural frequency analyses, the natural frequencies of the structural system and the mode shapes they will take if stimulated at this frequency value were obtained. The first mode shape of the system has the shape with the lowest potential energy and, therefore, its elongation energy per unit is lower compared to others. In the formation of the second, third, and other modes, a constantly increasing internal strain energy is needed. In practical applications, the first natural frequency is generally the most important one. Its

frequency is the most easily accessible and easily controlled through interventions in design parameters. Fig. 2f shows the image at the highest frequency value (9.7049 Hz. Here, the highest total deformation value was calculated as 0.0021247 m. In the first, second, and fourth mode shapes of the bridge, a deflection effect is observed. In the third, fifth, and sixth modes of the bridge, deflection and torsion effects are observed in conjunction.

Deformation results were obtained in the harmonic analysis application with load values of 60 kN, 90 kN, and 120 kN applied by taking the number of vehicles on the Kuşsarayı-2 Bridge as four, six, and eight, and it was observed that the results increased in parallel with the load value. According to the deformation results obtained, the maximum deformation value on the bridge was calculated as 0.00091778 m, and it was observed that this value was recorded at exactly the center line of the bridge. Fig. 3 shows the bridge visual in which the bridge under this load is exposed to maximum deformation. At the center section of the bridge, a total of 9 Bimorph PEHs were placed vertically in the direction of the road with one under each beam, and this image is shown in Fig. 4.

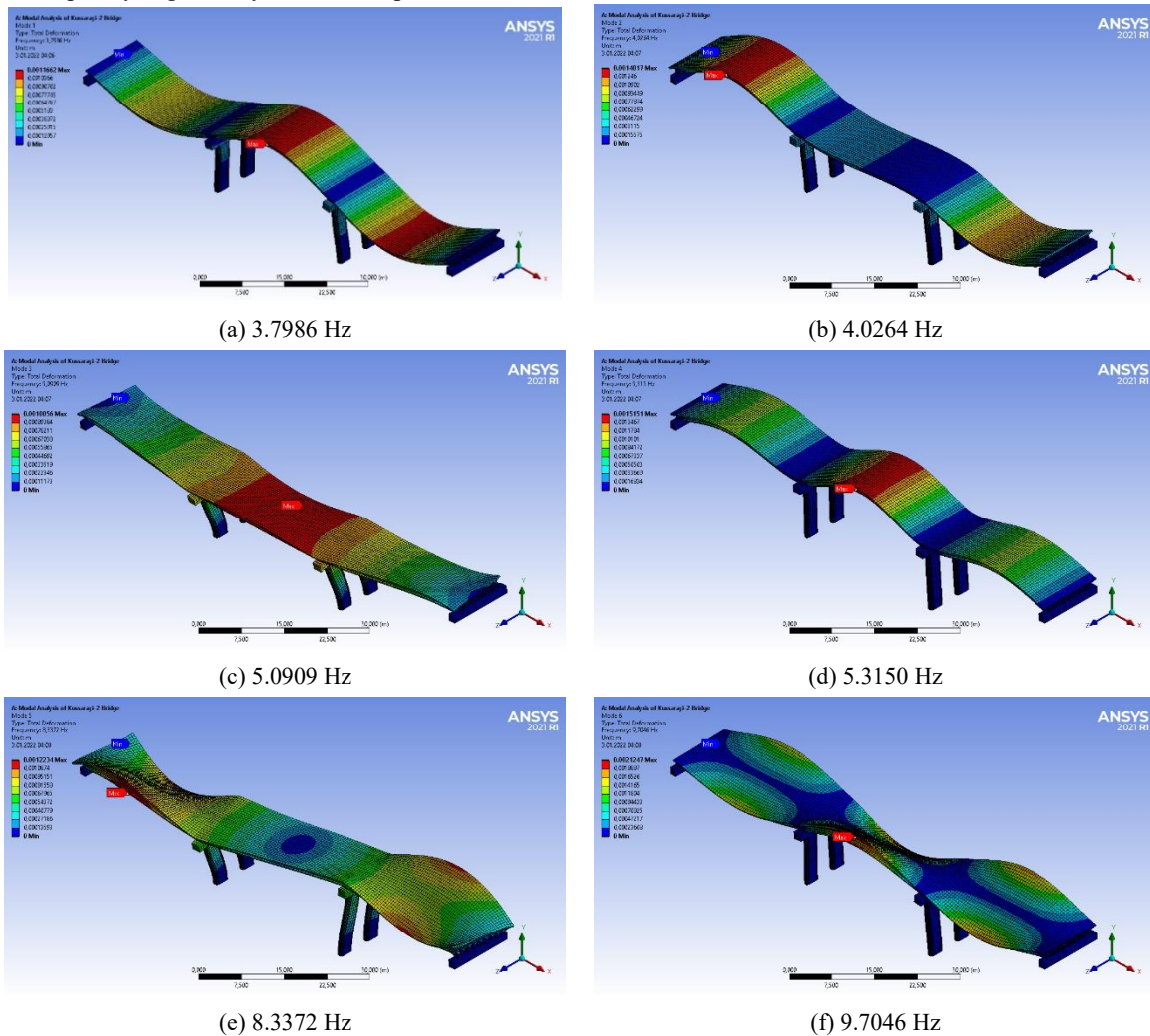


Fig. 2. The total deformation image at the natural frequencies of the bridge

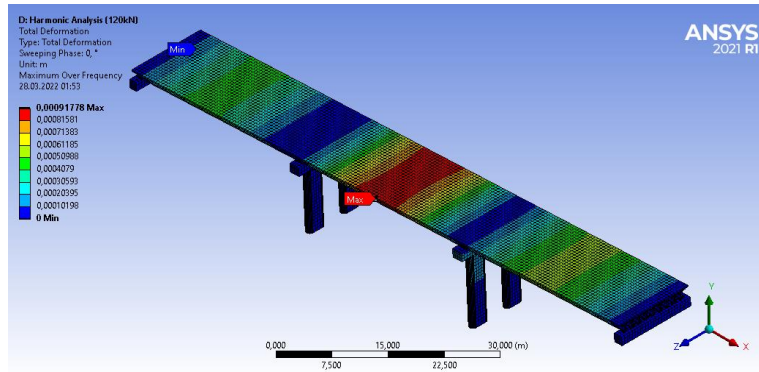


Fig. 3. Total deformation image as a result of the harmonic analysis performed under a load value of 120 kN

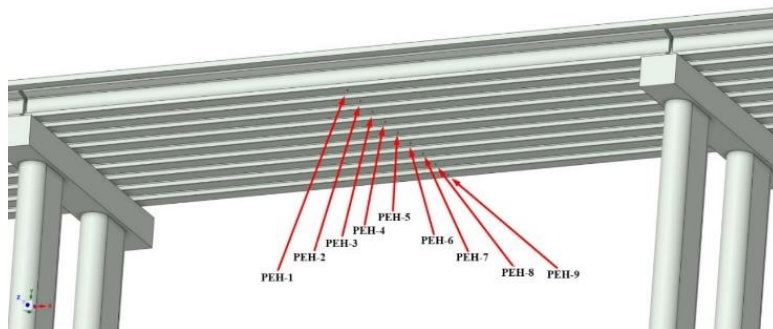


Fig. 4. Image of the positions of the PEHs on the bridge

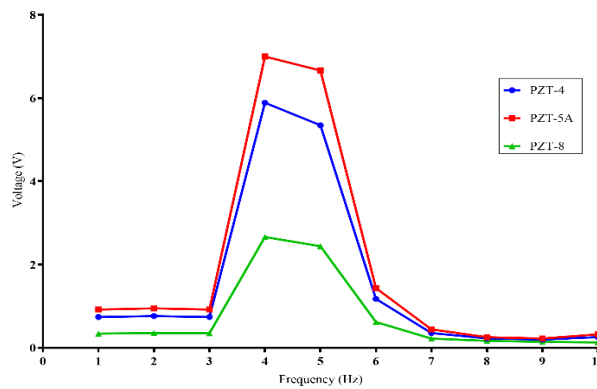


Fig. 5. The change in voltage frequency for PEH-1 under a load of 120 kN based on different types of material

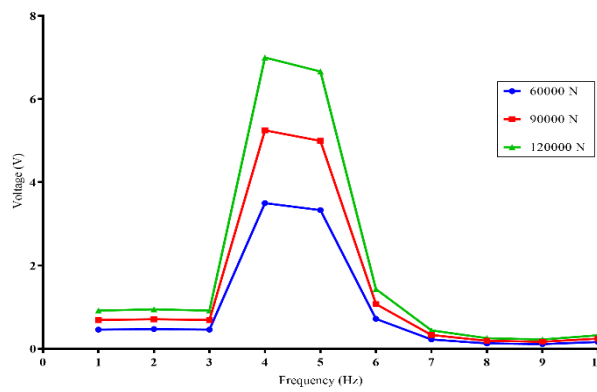


Fig. 6. The change in voltage frequency for PZT-5A under different loads, PEH-1

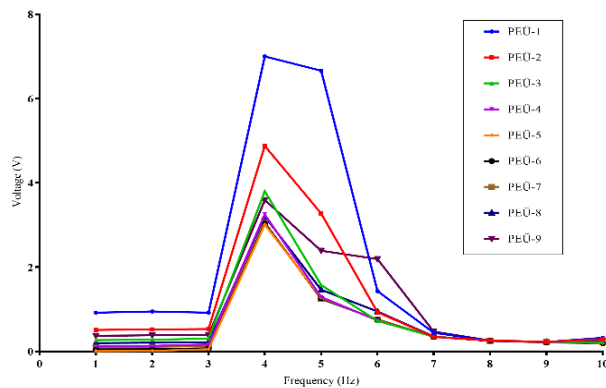


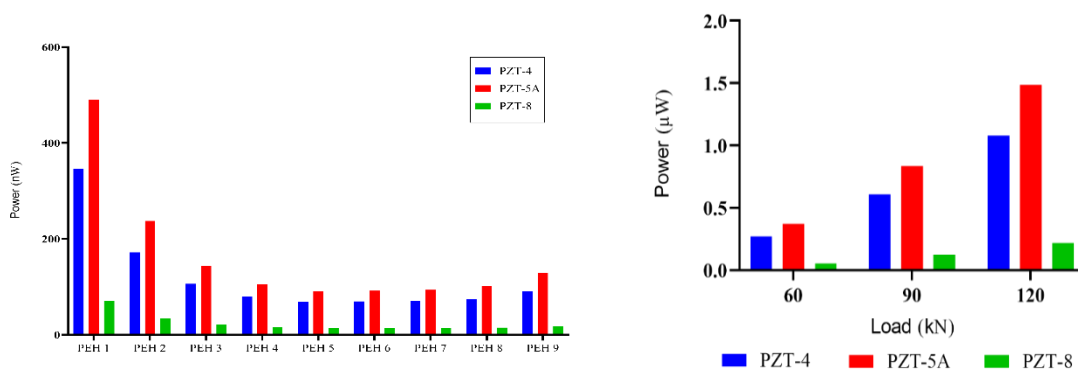
Fig. 7. The change in voltage frequency for the PEHs type PZT-5A under a load of 120 kN

Table 3. Maximum voltage values (V) produced by the PEHs

PEH type	PZT-4			PZT-5A			PZT-8		
	60 kN	90 kN	120 kN	60 kN	90 kN	120 kN	60 kN	90 kN	120 kN
PEH-1	2.9435	4.4152	5.8869	3.4992	5.2488	6.9984	1.3300	1.9950	2.6600
PEH-2	2.0732	3.1098	4.1463	2.4377	3.6566	4.8754	0.9343	1.4014	1.8686
PEH-3	1.6311	2.4467	3.2622	1.8987	2.8480	3.7973	0.7333	1.0999	1.4665
PEH-4	1.4060	2.1090	2.8120	1.6241	2.4362	3.2482	0.6309	0.9464	1.2618
PEH-5	1.3127	1.9690	2.6254	1.5054	2.2582	3.0109	0.5857	0.8785	1.1714
PEH-6	1.3203	1.9805	2.6406	1.5156	2.2734	3.0311	0.5889	0.8833	1.1778
PEH-7	1.3310	1.9966	2.6621	1.5296	2.2944	3.0592	0.5934	0.8901	1.1868
PEH-8	1.3627	2.0441	2.7254	1.5993	2.3989	3.1985	0.6083	0.9124	1.2165
PEH-9	1.5040	2.2560	3.0080	1.7951	2.6927	3.5902	0.6680	1.0021	1.3361

Table 4. Maximum power (nW) produced by the piezoelectric energy harvesters

PEH type	PZT-4			PZT-5A			PZT-8		
	60 kN	90 kN	120 kN	60 kN	90 kN	120 kN	60 kN	90 kN	120 kN
PEH-1	86.642	194.940	346.556	122.444	275.499	489.776	17.689	39.800	70.756
PEH-2	42.982	96.709	171.918	59.424	133.707	237.695	8.729	19.639	34.917
PEH-3	26.605	59.863	106.419	36.051	81.111	144.195	5.377	12.098	21.506
PEH-4	19.768	44.479	79.073	26.377	59.351	105.508	3.981	8.956	15.921
PEH-5	17.232	38.770	68.927	22.662	50.995	90.655	3.430	7.718	13.722
PEH-6	17.432	39.224	69.728	22.970	51.683	91.876	3.468	7.803	13.872
PEH-7	17.716	39.864	70.868	23.397	52.643	93.587	3.521	7.923	14.085
PEH-8	18.570	41.783	74.278	25.578	57.547	102.304	3.700	8.324	14.799
PEH-9	22.620	50.895	90.481	32.224	72.506	128.895	4.463	10.042	17.852
Total	269.566	606.527	1078.248	371.126	835.042	1484.491	54.357	122.304	217.429



(a) Maximum power changes of the PEHs

(b) Total power change of the PEHs

Fig. 8. Power of the PEHs

To produce energy from piezoelectric systems, a total of 9 PEHs were analyzed with various types of PZT (PZT-4, PZT-5A, and PZT-8) using the results obtained from the harmonic analysis. As a result of this analysis, the maximum voltage value of the PEHs was measured at a frequency of 4 Hz. When the results were compared, it was observed that the voltage magnitudes obtained were formed in the PEHs type PZT-5A, PZT-4, and PZT-8, respectively, and that the results increased in direct proportion for loads of 60 kN, 90 kN, and 120 kN applied, as well. Figs. 5 and 6 show the results obtained with various vehicle loads and PZT types in PEH-1, in which the highest stress occurred, with comparative graphs. Fig. 7 shows the results obtained from the PEH type PZT-5A under a load of 120 kN, in which maximum stress occurred.

Table 3 shows the maximum voltage values produced by PEHs type PZT-4, PZT-5A, and PZT-8 under loads of 60 kN, 90 kN, and 120 kN. The maximum amounts of power produced by the PEHs were calculated using maximum voltage values, and the results obtained are shown in Table 4. Fig. 8a shows the results in the form of a comparative graphic.

When the PZT types were examined in the piezoelectric analysis performed, it was observed that the highest power was produced in PZT-5A, and a maximum power of 1.484  $\mu\text{W}$  was obtained from the PEH type PZT-5A under a load of 120 kN. Fig. 8b shows the results.

When previous studies are examined, in the study conducted by Peigney and Siegert [20], measurements were made by experimentally placing PEHs on pipes under a bridge with vehicles passing without calculating the optimal locations, and the maximum voltage in the PEH was found as 3.6 V, while the maximum power was found as 0.03 mW [20]. In the study conducted by Balgavhar and Bhalla [39], PEHs were experimentally placed in a non-optimal location under an urban overpass, and at 4 Hz, at which maximum stress was observed, the voltage obtained from the PEH was 4 V while the power was 0.20  $\mu\text{W}$ .

The highest results from the PEHs placed at optimal locations were calculated as a maximum voltage output of 7 V and a maximum power value of 0.49  $\mu\text{W}$  from PEH-1 type PZT-5A under a load of 120 kN. These results also demonstrate that piezoelectric energy harvesting can effectively contribute to sustainable smart infrastructure solutions, highlighting its potential to support self-powered monitoring, extend the lifespan of structures, and reduce dependence on external energy sources. While previous studies in the literature [20, 39] generally utilized random or experimental placement regarding PEHs on bridges, this study specifically employed finite element analysis to determine the exact optimal locations (maximum deformation points) before placement. This approach allows for higher energy harvesting efficiency relative to the structural geometry compared to non-optimized placement methods.

## 4. Conclusions

The vibration that occurs in bridge structures due to the passage of vehicles can be transformed into useful electric power using PEHs. In the present study, energy harvesting was achieved by detecting the optimal locations of PEHs in the Kuşsarayı-2 Bridge. In the study, energy was harvested from the vibrations in the bridge structure using three different vehicle loads and three different piezoelectric materials. The modal analysis of the Kuşsarayı-2 Bridge was solved, and the natural frequencies were found as 3.7986, 4.0264, 5.0909, 5.3150, 8.3372, and 9.7049 Hz. The maximum total deformation obtained at the lowest natural frequency value (3.7986 Hz) was calculated as 0.0011662 m, while the maximum total deformation at the highest natural frequency value (9.7049 Hz) was calculated as 0.0021247 m.

In order to perform the optimal placement of the PEHs to be used in energy harvesting, harmonic analysis was carried out, and the maximum deformation value was found as 0.00091778 m while the maximum location was detected as the center line of the bridge. To produce energy from piezoelectricity, Bimorph PEHs were designed to be placed under the beams on the bridge. Three different piezoelectric materials (PZT-4, PZT-5A, and PZT-8) were used for a total of 9 Bimorph PEHs placed vertically in the direction of the road with one under each beam at the center section of the bridge, and a total of 13 analyses were performed under three different vehicle loads (60 kN, 90 kN and 120 kN) to compare the results. In PEH-1, which exhibited the highest stress value, the maximum stress was calculated as 7 V while the maximum power was found as 0.49  $\mu\text{W}$ . As a result of the analyses, it was found that when PEH type PZT-8 is used in a bridge structure under a load of 120 kN, which equals the load of 8 vehicles, the total maximum power is 0.217  $\mu\text{W}$ , while this value is 1.078  $\mu\text{W}$  for PEH type PZT-4 and 1.484  $\mu\text{W}$  for PEH type PZT-5A. It was determined that the piezoelectric material with the highest energy harvesting was PZT-5A. When these energy production values are compared with the literature, it is observed that the results are moderate.

This power can be used in wireless sensor systems used to monitor the structural health of bridges, and if these systems are developed, the energy needs of services such as lighting and traffic signs in bridge structures can be supplied. Considering that energy harvesting by vibration is independent of weather conditions, unlike energy sources such as the sun and wind, the widespread use of these systems will prevent the environmental damage of waste batteries formed in existing systems. Today, it is necessary for these systems to be used in bridge designs, and CO<sub>2</sub> emissions can be reduced by achieving significant levels of harvesting from clean energy sources at a time when issues surrounding energy are increasing day by day.

## Declarations

## Conflict of interests

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

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## Author contributions

All authors contributed equally to this study. All authors have read and approved the final manuscript and accept equal responsibility for its content.

## Data availability statement

The data presented in this study are available on request from the corresponding author.

## Use of generative AI and AI-assisted technologies

The author(s) confirm the author(s) did not use any AI tools in the preparation of this work/research/study.

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