Properties and applications of piezoelectric materials

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Abstract

The piezoelectric effect is the phenomenon in which materials respond to applied mechanical stress by accumulating electric charge. This property allows piezoelectric materials to be utilised as an alternating voltage source when connected to an external circuit and applied force to. Therefore, energy harvesting devices can be constructed using piezoelectric materials to harness ambient mechanical energy and transform it into usable electrical energy. This investigation aimed to investigate the effect of load resistance on the voltage and power characteristics of a basic piezoelectric energy harvesting circuit, consisting of a full-wave rectifier with a smoothing capacitor, connected directly to a resistive load. The results showed that the output voltage from the rectifier, the RMS voltage from the piezoelectric transducer, and the power output from the rectifier all increased linearly with an increase in resistance within a range of $5.6*10^3$ Ω ± $3*10^2$ Ω to $5.4*10^4$ Ω ± $4*10^3$ Ω.

Introduction

The piezoelectric effect is the phenomenon in which materials respond to applied mechanical stress by accumulating electric charge (Xu et al., 2018). When a piezoelectric element is connected to an external circuit, it essentially acts as a voltage, current, charge, or power source when force is applied, allowing current to flow through the load. Therefore, piezoelectric materials can be utilised to create energy harvesting devices that convert ambient mechanical energy, such as vibrations from engines, household appliances, vehicles on roads, human footsteps, into usable electrical energy (Li & Lee, 2022). This is of importance due to the increasing need for renewable energy sources and carbon emission reduction. Furthermore, piezoelectric energy harvesters have the potential to be an alternative source of energy for low power devices in applications where replacing batteries is inconvenient, costly, or inaccessible, such as medical devices implanted in the human body, and devices in remote locations. By removing the need for battery replacements, waste from battery disposal is mitigated, allowing for a decreased environmental impact (Brusa et al., 2023).

When mechanical vibrations are applied to a piezoelectric transducer, it produces alternating current. Therefore, to utilise this for practical purposes, the voltage needs to be rectified into direct current, which is typically achieved by using a full-wave rectifier and a smoothing capacitor. The resulting DC voltage can either be used to charge energy storage devices or be supplied directly to a resistive load.

Rationale

Piezoelectric energy harvesting is a promising method of producing clean energy from ambient energy sources which have yet to be utilised extensively on a commercial scale. This investigation aims to investigate the potential of harnessing piezoelectricity as a usable source of electrical energy.

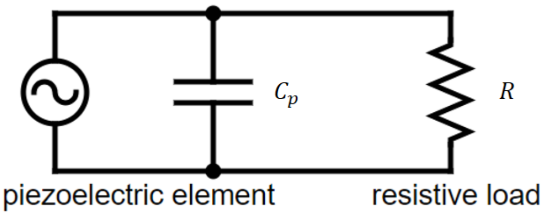
Aim

To investigate the effect of load resistance on the voltage and power characteristics of a basic piezoelectric energy harvesting circuit, consisting of a full-wave rectifier with a smoothing capacitor, connected directly to a resistive load.

Hypothesis

As resistance increases, the DC voltage output from the diode rectifier and the RMS voltage from the piezoelectric transducers will increase until a plateau is reached. The power output of the resistive load will also increase but will reach a peak and then decrease.

To justify this, a simplified model of a piezoelectric energy harvesting circuit will be used:



The piezoelectric element can be modelled as a sinusoidal source of charge, Q, in parallel with its internal capacitance, $\mathrm{C_p}$. The circuit is connected to a resistive load, R.

For the equivalent impedance, Z:

$$\frac{1}{Z} = \frac{1}{Z_C} + \frac{1}{R}$$

$$Z = \frac{Z_C R}{Z_C + R}$$

$$Z_C = \frac{1}{i\omega C_p}$$

$$\therefore Z = \frac{R}{i\omega C_p\left(\frac{1}{i\omega C_p} + R\right)} = \frac{R}{1 + i\omega R C_p}$$

The generalised Ohm's Law states that:

$V = IZ$, where V and I are the complex voltage and current, respectively, and Z is the complex impedance

$$\therefore V = I\left(\frac{R_L}{1 + i\omega R C_p}\right)$$

Given that $Q = Q_0 e^{i\omega t}$:

$$\frac{dQ}{dt} = i\omega Q_0 e^{i\omega t}$$

$$\frac{dQ}{dt} = i\omega Q$$

$$\therefore I = i\omega Q$$

$$\therefore V = \frac{i\omega RQ}{1+i\omega RC_p}$$

$$|V| = \frac{\omega RQ}{\sqrt{1+\left(\omega RC_p\right)^2}} \qquad (1)$$

$$|P| = \frac{|V|^2}{R}$$

$$\therefore |P| = \frac{\omega^2 RQ^2}{1+\left(\omega RC_p\right)^2} \qquad (2)$$

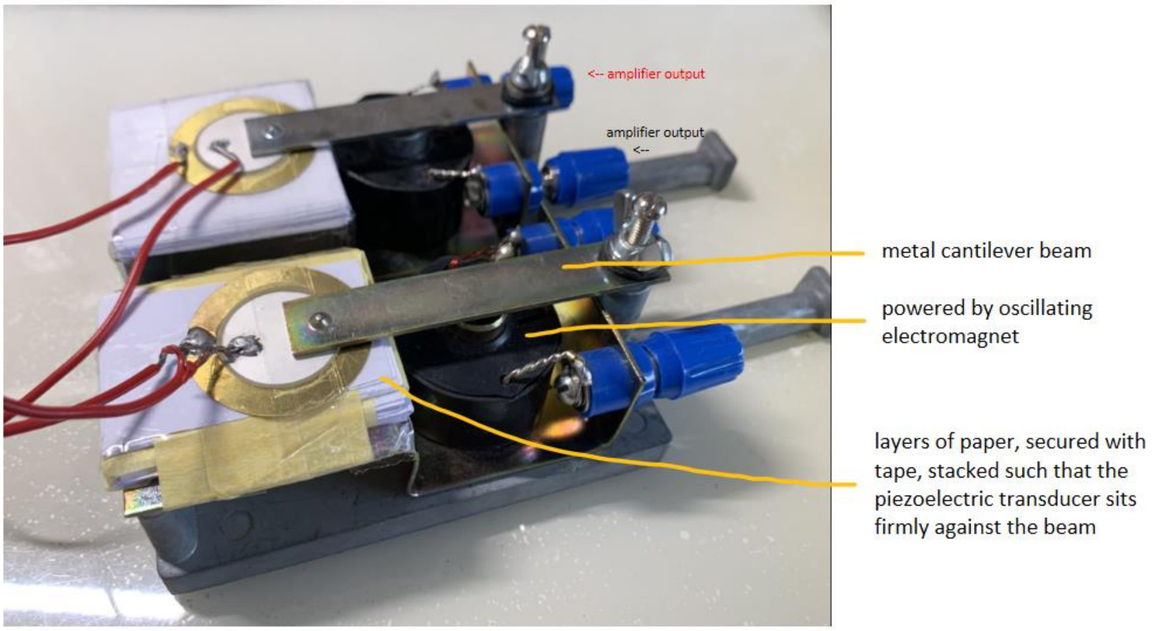
[adapted from Li and Lee (2022)]

Therefore, from equations (1) and (2), it can be seen that as resistance increases, the amplitude of the voltage from the piezoelectric element and the voltage across the resistor increases and asymptotes. The power output will increase until a peak is reached, and then decrease.

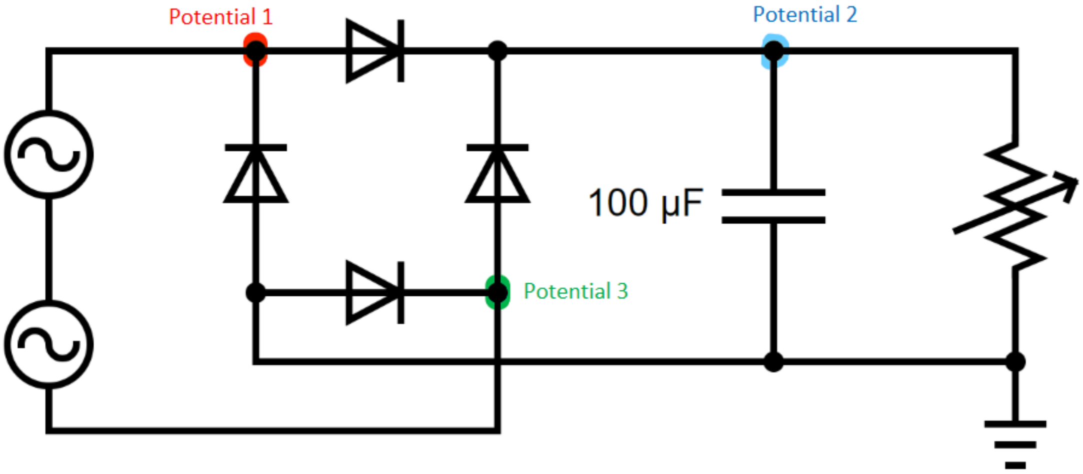
This result can be extended to qualitatively describe the characteristics of the circuit used in this investigation. The RMS voltage from the piezoelectric transducers is proportional to the amplitude, assuming the voltage output is sinusoidal. Assuming that the voltage drop across the diode rectifier is constant, the voltage outputfrom the rectifier should also be proportional to the amplitude. Therefore, given that power is derived from voltage, the general trend for power as described in equation (2) should also be observed.

Method

Ceramic piezoelectric transducer discs made of lead zirconate titanate (PZT) were used to power the circuit. Two transducers were soldered together in series, allowing for more voltage output. The setup below was used to provide mechanical vibrations to the transducers.

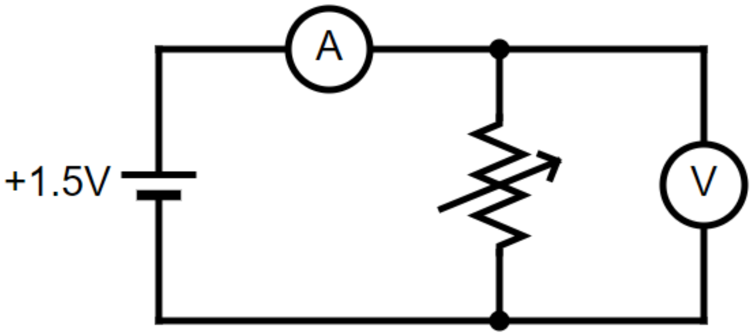


The devices were connected in parallel and powered by a function generator at approximately 50 Hz, connected to the inbuilt amplifier, which was kept at a fixed amplitude throughout the experiment.



A basic energy harvesting circuit was used, as shown above (pre-built diode bridge used). The diode bridge was soldered to the piezoelectric transducers, and the remaining components were connected by component holder clips and banana leads. Three voltage probes were used to measure voltage, all connected at ground and the three different points indicated. The voltage probes were zeroed prior to each set of trials by connecting the two leads to each other, creating a short circuit. A potentiometer, connected at its first two terminals, was used as a variable resistor.

To determine the resistance of the potentiometer, the following circuit was used to measure voltage and current before each trial. Multimeters were used as the voltmeter and ammeter.



Logger Pro was used for data collection. The function generator was switched on approximately 5 seconds after starting data collection. Once steady-state conditions were reached, data collection continued for around 15-20 seconds before the function generator was switched off. Once switched off, allow voltage to fall back to initial values before ending collection. Three trials were conducted for each resistance value.

Results

Table 1 – voltage and power characteristics at different resistance values

R (kΩ)	ΔR (kΩ)	Vout (V)	ΔVout (V)	Vrms (V)	ΔVrms (V)	efficiency	Δη	P (nW)	ΔP (nW)
5.6	3	0.021	0.005	0.569	0.014	0.037	0.010	8.1	4.2
8.7	6	0.0375	0.0006	0.63	0.02	0.060	0.003	16	1.6
14.2	9	0.050	0.003	0.635	0.008	0.079	0.005	18	3
18.2	1.2	0.0637	0.0013	0.660	0.002	0.097	0.002	22	2
22.5	1.2	0.082	0.005	0.699	0.006	0.117	0.007	30	5
27.8	1.6	0.0929	0.0017	0.732	0.004	0.127	0.003	31	3
33	2	0.108	0.003	0.770	0.003	0.141	0.004	35	4
39	2	0.122	0.002	0.808	0.004	0.151	0.003	38	4
46	3	0.139	0.004	0.849	0.011	0.164	0.007	42	5
54	4	0.166	0.001	0.860	0.015	0.193	0.005	51	4

Figure 1 – DC voltage output from rectifier

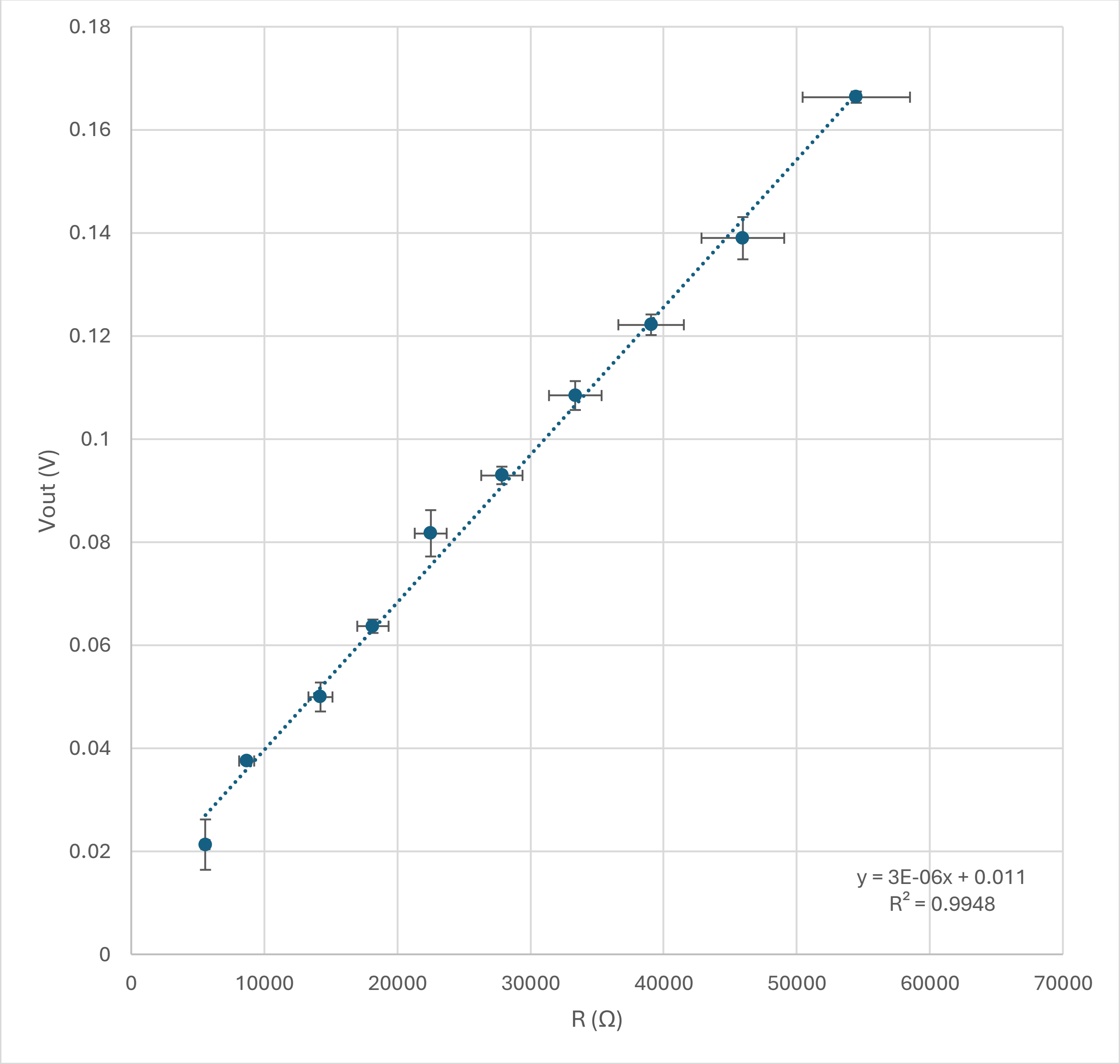


Figure 2 – RMS voltage from piezoelectric transducer

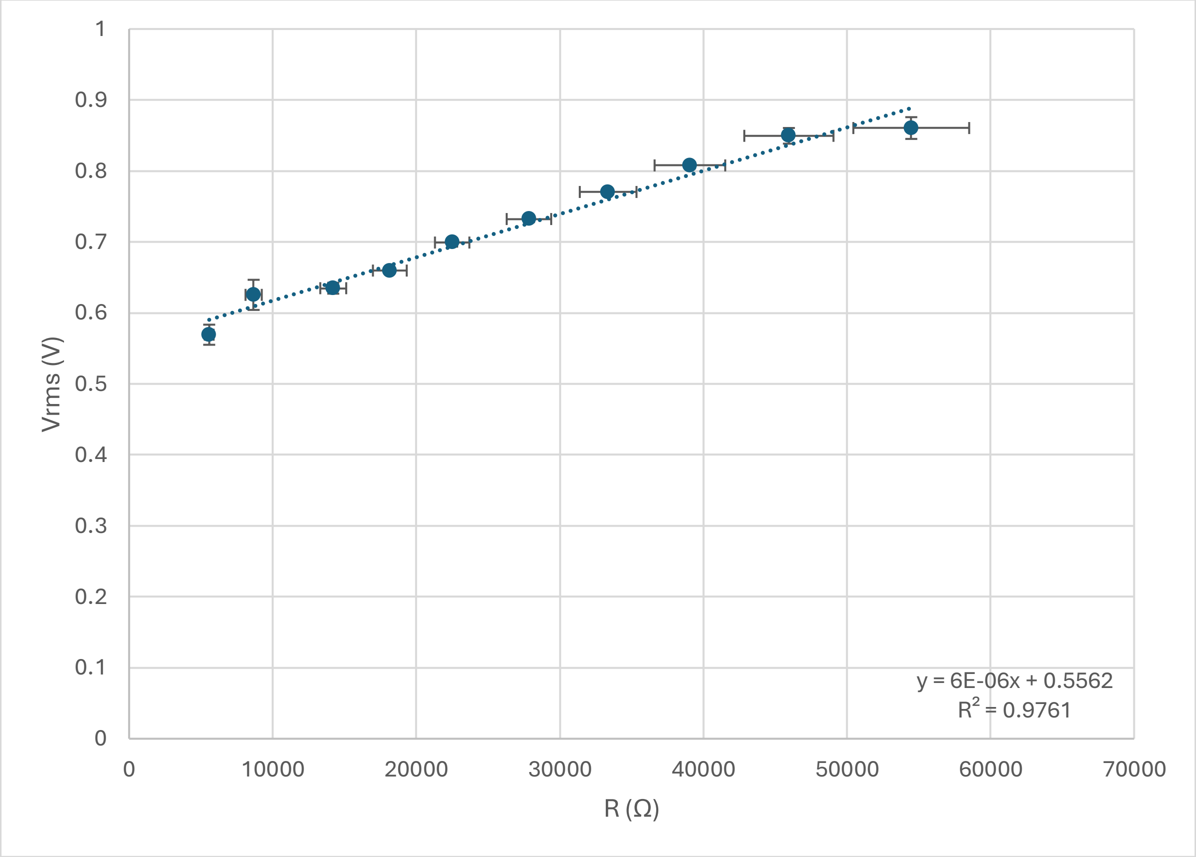


Figure 3 – power output from rectifier

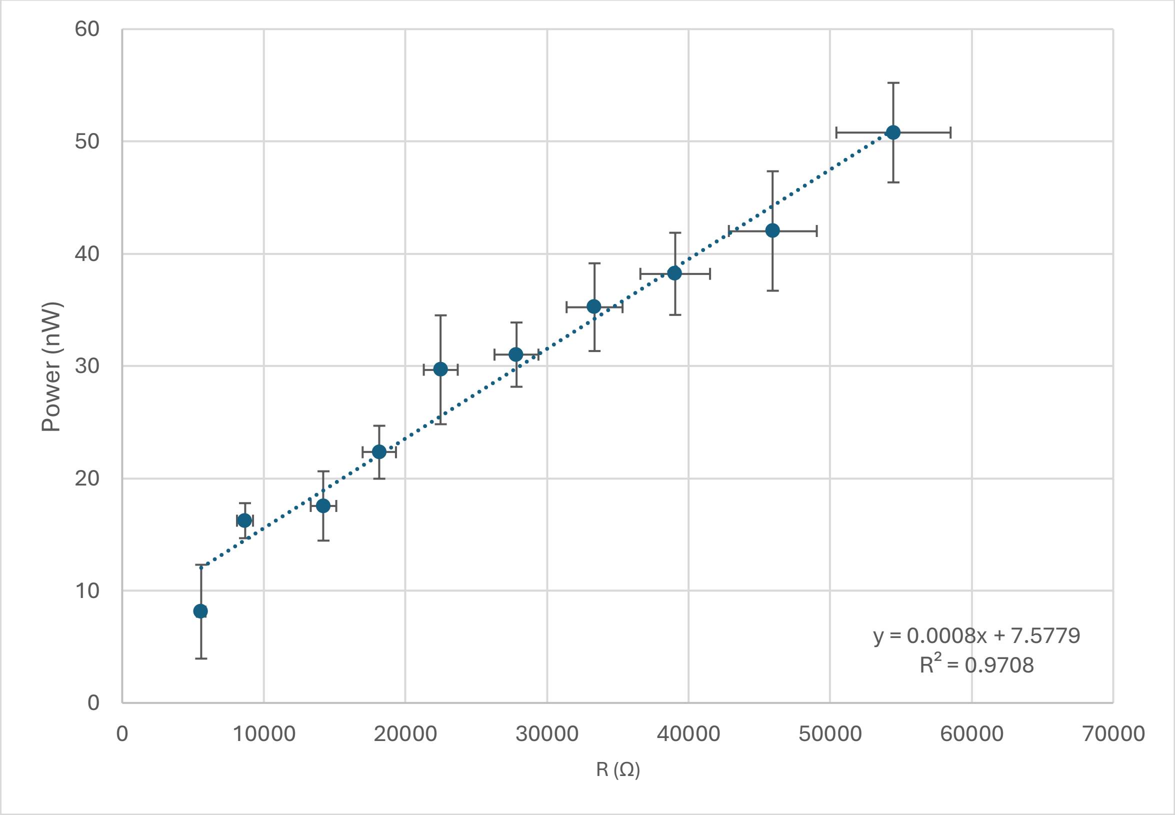
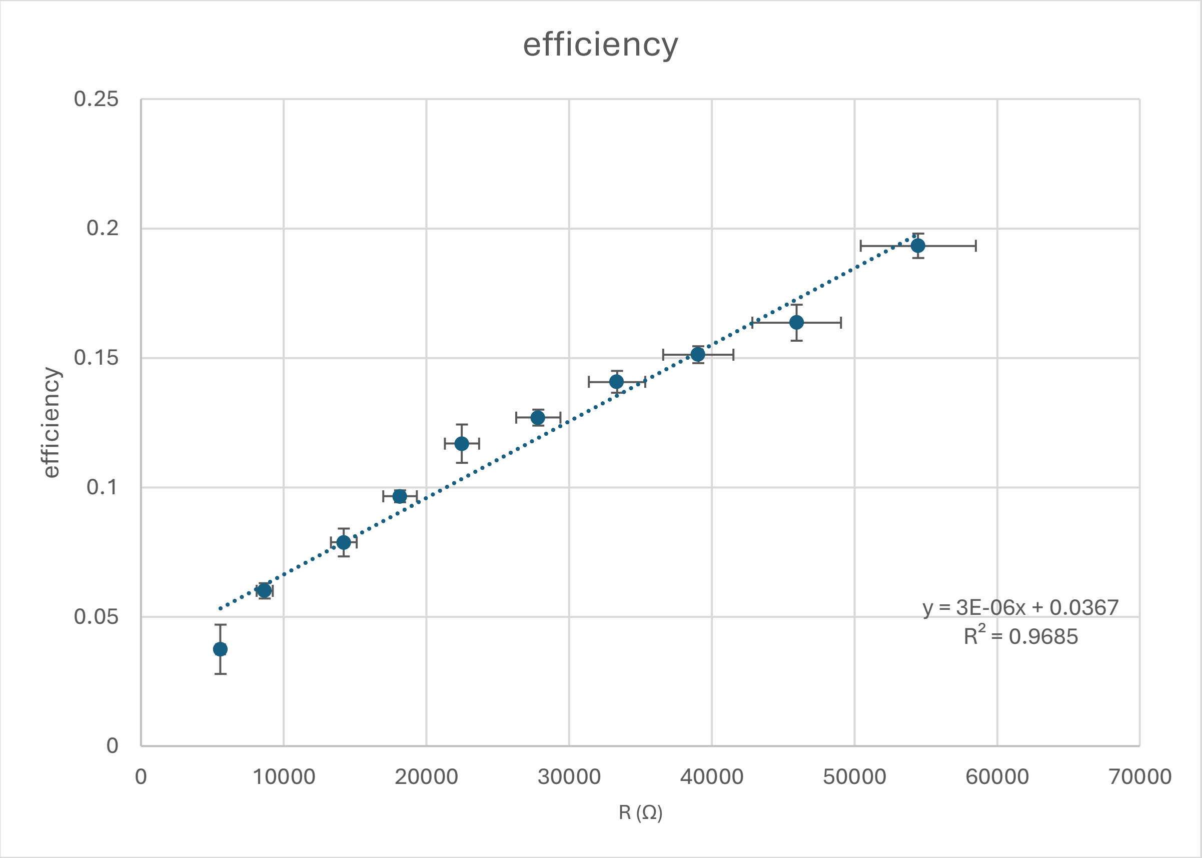
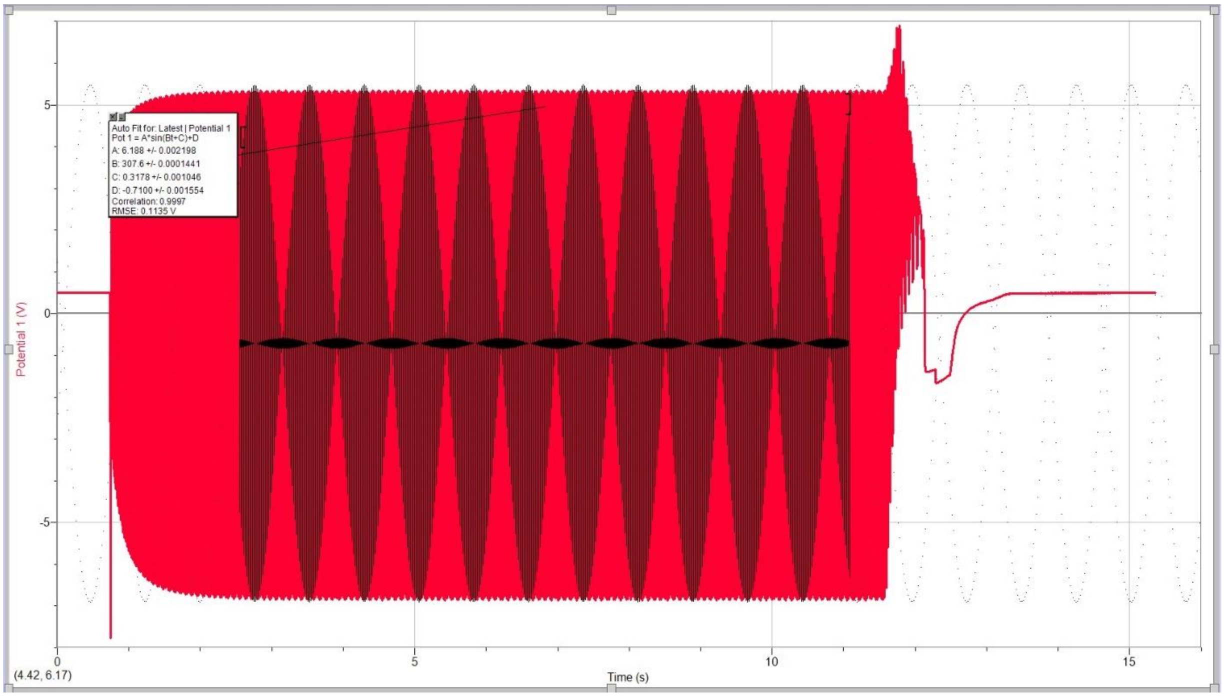


Figure 4 – efficiency ($V_{\mathrm{out}}/V_{\mathrm{rms}}$)



All trials were conducted at the same frequency (~50 Hz). To determine a more accurate value of frequency, the function generator was connected directly to a voltage probe. A sine wave function was fitted to the graph in Logger Pro.



```
Auto Fit for: Latest | Potential 1
Pot 1 = A*sin(Bt+C)+D
A: 6.188 +/- 0.002198
B: 307.6 +/- 0.0001441
C: 0.3178 +/- 0.001046
D: -0.7100 +/- 0.001554
Correlation: 0.9997
RMSE: 0.1135 V
```

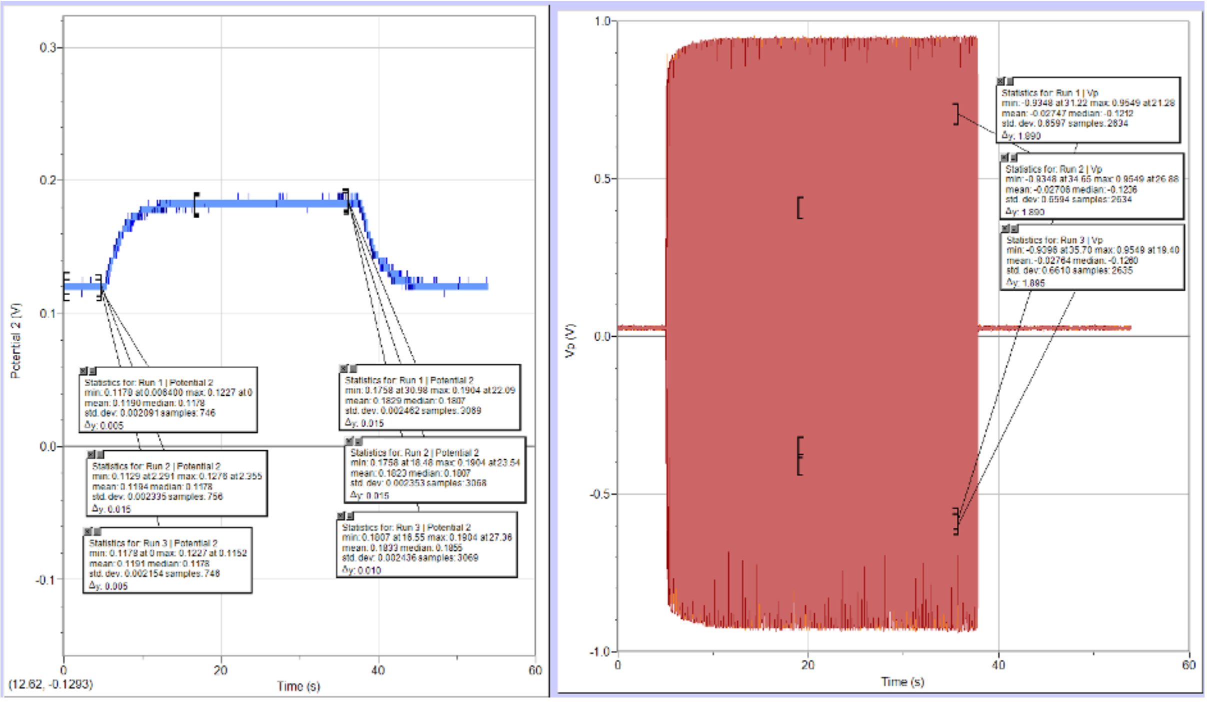
Using the coefficient B to determine frequency, f:

$$f = \frac{B}{2\pi}$$

$$f = \frac{307.6\ \mathrm{s}^{-1}}{2\pi}$$

$$f = 48.96\ \mathrm{Hz}$$

To derive voltage across the piezoelectric transducers (Vp), a difference in voltage was taken between Potential 1 and Potential 3.



```
Statistics for: Run 1 | Potential 2
min: 0.1178 at 0.008400 max: 0.1227 at 0
mean: 0.1190 median: 0.1178
std. dev: 0.002091 samples: 746
Δy: 0.005

Statistics for: Run 2 | Potential 2
min: 0.1129 at 2.291 max: 0.1278 at 2.355
mean: 0.1194 median: 0.1178
std. dev: 0.002335 samples: 756
Δy: 0.015

Statistics for: Run 3 | Potential 2
min: 0.1178 at 0 max: 0.1227 at 0.1152
mean: 0.1191 median: 0.1178
std. dev: 0.002154 samples: 748
Δy: 0.005

Statistics for: Run 1 | Potential 2
min: 0.1758 at 30.98 max: 0.1904 at 22.09
mean: 0.1829 median: 0.1807
std. dev: 0.002462 samples: 3089
Δy: 0.015

Statistics for: Run 2 | Potential 2
min: 0.1758 at 18.48 max: 0.1904 at 23.54
mean: 0.1823 median: 0.1807
std. dev: 0.002353 samples: 3068
Δy: 0.015

Statistics for: Run 3 | Potential 2
min: 0.1807 at 18.55 max: 0.1904 at 27.36
mean: 0.1833 median: 0.1855
std. dev: 0.002436 samples: 3069
Δy: 0.010

Statistics for: Run 1 | Vp
min: -0.9348 at 31.22 max: 0.9549 at 21.28
mean: -0.02747 median: -0.1212
std. dev: 0.6597 samples: 2634
Δy: 1.890

Statistics for: Run 2 | Vp
min: -0.9348 at 34.65 max: 0.9549 at 26.88
mean: -0.02706 median: -0.1236
std. dev: 0.6594 samples: 2634
Δy: 1.890

Statistics for: Run 3 | Vp
min: -0.9396 at 35.70 max: 0.9549 at 19.40
mean: -0.02764 median: -0.1260
std. dev: 0.6610 samples: 2635
Δy: 1.895
```

V_i was calculated from the mean voltage before the function generator was switched on. V_f was calculated from the mean voltage at steady-state conditions. V_{min} and V_{max} were taken as the minimum and maximum values of voltage at steady-state conditions.

For each individual trial, the following derived data points were calculated as follows:

$$V_{out} = V_f - V_i$$

$$V_{p-p} = V_{max} - V_{min}$$

$$V_{amp} = \frac{V_{p-p}}{2}$$

$$V_{rms} = \sqrt{\frac{1}{n}\sum_{i} x_i^2}$$

where x_i is each value of voltage within the time interval for steady-state conditions, and n is the number of measurements in that interval

The mean was taken across the three trials, and the uncertainty for each of the above values was taken to be the range across the three trials.

To calculate R of potentiometer:

$R = \frac{V}{I}$ (Ohm's Law)

The uncertainties for V and I are due to the limitations in multimeter quality and the resolution of the reading. The uncertainty for R was propagated as follows:

$$\Delta R = R\left(\frac{\Delta I}{I} + \frac{\Delta V}{V}\right)$$

Further derived quantites were calculated as follows:

$\eta = \frac{V_{out}}{V_{rms}}$ (efficiency)

$$\Delta\eta = \eta\left(\frac{\Delta V_{out}}{V_{out}} + \frac{\Delta V_{rms}}{V_{rms}}\right)$$

$$P = \frac{V_{out}^2}{R}$$

$$\Delta P = P\left(\frac{\Delta R}{R} + \frac{2\Delta V_{out}}{V_{out}}\right)$$

Discussion

The results show that an increase in the value of the resistive load from $5.6*10^3$ Ω ± $3*10^2$ Ω to $5.4*10^4$ Ω ± $4*10^3$ Ω corresponds to a linear increase in the voltage output from the diode rectifier, V_{out}, from 0.021 V ± 0.005 V to 0.166 V ± 0.001 V, a linear increase in the RMS voltage of the piezoelectric transducers, V_{rms}, from 0.569 V ± 0.014 V to 0.860 V ± 0.015 V, and a linear increase in the power output from the diode rectifier from 8.1 nW ± 4.2 nW to 50 nW ± 4 nW. These trends correspond to what is described by equations (1) and (2) for low values of R. However, the plateau for the voltages is not observed, and neither is the peak for power. This suggests that the range of resistances was insufficiently large for these trends to be observed.

Higher values of resistance were not investigated due to amplitude modulation occurring in the voltage output of the piezoelectric transducers, which would have yielded inaccurate values for V_{rms}, relative to a purely sinusoidal voltage output. The cause of this is unclear, given that two in phase sinusoidal voltage sources should constructively interfere, but may be due to resonance in the metal beam or in the circuit.

An increase in resistance also corresponds to an increase in efficiency, which is a ratio of V_{out} to V_{rms}. This may be due to the fixed voltage drop across the diode bridge. As V_{rms} increases, a smaller proportion of voltage is lost across the diodes, allowing for a greater proportion to be output from the rectifier, hence increasing efficiency. Therefore, to maximise voltage and power output to the load with this circuit configuration, a greater load resistance would be ideal.

Conclusion

This investigation found that an increase in the resistance of the piezoelectric energy harvesting circuit load from $5.6*10^3$ Ω ± $3*10^2$ Ω to $5.4*10^4$ Ω ± $4*10^3$ Ω correlates to a linear increase in the DC voltage output from the rectifier (0.021 V ± 0.005 V to 0.166 V ± 0.001 V), the RMS voltage of the piezoelectric transducer (0.569 V ± 0.014 V to 0.860 V ± 0.015 V), and the power output from the rectifier (8.1 nW ± 4.2 nW to 50 nW ± 4 nW). This somewhat supports the hypothesis that an increase in these values would be observed as resistance is increased, but a plateau in V_{out} and V_{rms} was not observed, and neither was a peak in power output. For future investigations, the aim could be investigated more thoroughly by possibly developing a more stable mechanism for the mechanical excitation of the piezoelectric transducers to allow the effect of greater resistive loads on the circuit's voltage characteristics to be examined.

References

Brusa, E., Carrera, A., & Delprete, C. (2023). A Review of Piezoelectric Energy Harvesting: Materials, Design, and Readout Circuits. *Actuators*, *12*(12), 457–457. https://doi.org/10.3390/act12120457

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Oral presentation video

https://www.dropbox.com/scl/fi/s5j6n21y0h56aepur4r6f/Video_DengJacqueline_Properties_and_Applications_of_Piezoelectric_Materials_OR-1-1654.mov?rlkey=j5ivxljzg4zdj1ohoi2al6fsn&dl=0

Appendix I – Raw data

Table 2 – Potentiometer data

	V (+/- 0.05 V)	I (A)	ΔI (A)	R (Ω)	ΔR (Ω)	ΔR/R
1	1.411	2.59E-05	1.00E-06	5.45E+04	4.03E+03	7.40E-02
2	1.42	3.09E-05	1.00E-06	4.60E+04	3.11E+03	6.76E-02
3	1.414	3.62E-05	1.00E-06	3.91E+04	2.46E+03	6.30E-02
4	1.408	4.22E-05	1.00E-06	3.34E+04	1.98E+03	5.92E-02
5	1.398	5.02E-05	1.00E-06	2.78E+04	1.55E+03	5.57E-02
6	1.386	6.16E-05	1.00E-06	2.25E+04	1.18E+03	5.23E-02
7	1.371	7.55E-05	1.00E-06	1.82E+04	9.03E+02	4.97E-02
8	1.436	1.01E-04	5.00E-06	1.42E+04	1.20E+03	8.43E-02
9	1.431	1.65E-04	5.00E-06	8.67E+03	5.66E+02	6.52E-02
10	1.417	2.54E-04	5.00E-06	5.58E+03	3.07E+02	5.50E-02

Table 3 – data for individual trials

	Vi (V)			**Vf (V)**			**Vmax (V)**			**Vmin (V)**		
R (Ω)	*T1*	*T2*	*T3*	*T1*	*T2*	*T3*	*T1*	*T2*	*T3*	*T1*	*T2*	*T3*
5578.74	0.03893	0.03082	0.0351	0.05947	0.05493	0.05432	0.8243	0.8292	0.8337	-0.8044	-0.8093	-0.8145
8672.727	0.05869	0.05761	0.0573	0.09589	0.09518	0.09508	0.8771	0.9064	0.9015	-0.853	-0.8771	-0.8817
14217.82	0.09516	0.09512	0.09491	0.1446	0.1439	0.1465	0.9161	0.9161	0.921	-0.9009	-0.8911	-0.9058
18158.94	0.119	0.1194	0.1191	0.1829	0.1823	0.1833	0.9549	0.9549	0.9549	-0.9348	-0.9348	-0.9396
22500	0.1462	0.1464	0.1463	0.2257	0.2304	0.2279	1.004	1.009	1.004	-0.9778	-0.9827	-0.9827
27848.61	0.1794	0.1795	0.1794	0.2731	0.2715	0.2725	1.057	1.052	1.057	-1.031	-1.031	-1.031
33364.93	0.2159	0.2142	0.2141	0.3227	0.3231	0.3237	1.109	1.104	1.109	-1.08	-1.085	-1.085
39060.77	0.247	0.248	0.2477	0.3699	0.3707	0.3686	1.153	1.153	1.148	-1.128	-1.133	-1.128
45954.69	0.2858	0.2866	0.2873	0.4238	0.424	0.4288	1.207	1.211	1.216	-1.181	-1.191	-1.196
54478.76	0.3344	0.3343	0.3348	0.5013	0.5006	0.5006	1.279	1.279	1.279	-1.254	-1.253	-1.253

	Vout (V)			**Vp-p (V)**			**Vamp (V)**			**Vrms (V)**		
R (Ω)	*T1*	*T2*	*T3*	*T1*	*T2*	*T3*	*T1*	*T2*	*T3*	*T1*	*T2*	*T3*
5578.74	0.02054	0.02411	0.01922	1.6287	1.6385	1.6482	0.81435	0.81925	0.8241	0.564098	0.565392	0.578254
8672.727	0.0372	0.03757	0.03778	1.7301	1.7835	1.7832	0.86505	0.89175	0.8916	0.611285	0.632501	0.63247
14217.82	0.04944	0.04878	0.05159	1.817	1.8072	1.8268	0.9085	0.9036	0.9134	0.633104	0.631738	0.639442
18158.94	0.0639	0.0629	0.0642	1.8897	1.8897	1.8945	0.94485	0.94485	0.94725	0.659747	0.658468	0.660745
22500	0.0795	0.084	0.0816	1.9818	1.9917	1.9867	0.9909	0.99585	0.99335	0.696131	0.70194	0.699409
27848.61	0.0937	0.092	0.0931	2.088	2.083	2.088	1.044	1.0415	1.044	0.733696	0.729316	0.733679
33364.93	0.1068	0.1089	0.1096	2.189	2.189	2.194	1.0945	1.0945	1.097	0.769001	0.769981	0.772213
39060.77	0.1229	0.1227	0.1209	2.281	2.286	2.276	1.1405	1.143	1.138	0.807159	0.81025	0.806075
45954.69	0.138	0.1374	0.1415	2.388	2.402	2.412	1.194	1.201	1.206	0.845064	0.847243	0.856122
54478.76	0.1669	0.1663	0.1658	2.533	2.532	2.532	1.2665	1.266	1.266	0.852858	0.860294	0.868186

	mean				*uncertainties*			
R (Ω)	**Vout (V)**	**Vp-p (V)**	**Vamp (V)**	**Vrms (V)**	**ΔVout (V)**	**ΔVp-p (V)**	**ΔVamp (V)**	**ΔVrms (V)**
5578.74	0.02129	1.638467	0.819233	0.569248	0.00489	0.0195	0.00975	0.014155763
8672.727	0.037517	1.7656	0.8828	0.625419	0.00058	0.0534	0.0267	0.021216025
14217.82	0.049937	1.817	0.9085	0.634762	0.00281	0.0196	0.0098	0.007703936
18158.94	0.063667	1.8913	0.94565	0.659653	0.0013	0.0048	0.0024	0.002276772
22500	0.0817	1.986733	0.993367	0.69916	0.0045	0.0099	0.00495	0.005808705
27848.61	0.092933	2.086333	1.043167	0.73223	0.0017	0.005	0.0025	0.004380678
33364.93	0.108433	2.190667	1.095333	0.770398	0.0028	0.005	0.0025	0.003211835
39060.77	0.122167	2.281	1.1405	0.807828	0.002	0.01	0.005	0.004175534
45954.69	0.138967	2.400667	1.200333	0.849477	0.0041	0.024	0.012	0.011058159
54478.76	0.166333	2.532333	1.266167	0.860446	0.0011	0.001	0.0005	0.015327862