

Supplementary Information

Maximizing the Voltage Output of Piezoelectric Arrays via Base Layer Compatibility

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Overview

This supplementary document presents detailed voltage metrics obtained from energy harvesting experiments using a single Piezoelectric Transducer (PZT) and three PZTs connected in series. The experiments were conducted on 13 different base layers, including four homogeneous materials—Polycarbonate Sheet, Acrylic Sheet, PE Foam, and PETG—as well as nine metamaterial-based structures: Rectilinear, Honeycomb, and Gyroid, each tested with 10%, 20%, and 30% infill ratios.

Each base layer configuration was subjected to 35 independent trials, ensuring comprehensive data collection for performance evaluation. The tables that follow provide a comparative analysis of the harvested voltage for each base layer under both PZT configurations. These results offer insights into the impact of material composition, structural design, and PZT arrangement on energy harvesting efficiency. The recorded voltage data serves as a reference for assessing the repeatability and reliability of the energy harvesting process under controlled conditions.

Supplementary Table 1 The table shows the multiple trails (Open Circuit Voltages) for Polycarbonate sheet using single and 3 PZTs connected in series.

Polycarbonate Sheet	VO (V)	VO (V) – 3 PZT
1	3.60	6.50
2	2.90	7.40
3	3.80	6.80
4	3.70	6.00
5	3.00	7.40
6	3.30	6.30
7	4.20	6.80
8	3.50	5.70
9	2.80	6.00
10	2.90	7.20
11	3.10	9.50
12	3.20	5.70
13	3.00	6.50
14	3.30	10.50
15	3.70	6.50
16	4.00	9.70
17	4.40	4.90
18	3.00	5.50
19	2.50	10.20
20	3.00	9.70
21	2.90	9.50
22	2.80	5.90
23	3.50	7.80
24	3.40	7.50
25	4.00	5.90
26	3.00	6.20
27	2.90	7.50
28	3.70	8.70
29	4.00	6.50
30	3.00	7.20
31	4.20	7.50
32	4.40	8.00
33	3.80	9.40
34	2.75	10.00
35	2.80	9.60
Average	3.37	7.49
Standard Deviation	0.53	1.58

Supplementary Table 2 The table shows the multiple trails (Open Circuit Voltages) for acrylic sheet using single and 3 PZTs connected in series.

Acrylic Sheet	VO (V)	VO (V) – 3 PZT
1	3.60	7.60
2	2.10	7.00
3	2.80	7.20
4	3.50	5.70
5	3.40	4.40
6	2.00	6.50
7	4.00	5.80
8	3.00	5.70
9	3.50	4.90
10	2.20	7.20
11	1.80	8.00
12	2.70	5.70
13	2.80	6.50
14	2.60	7.70
15	2.20	6.50
16	2.10	9.70
17	3.50	4.20
18	3.60	4.10
19	3.30	4.50
20	2.80	5.10
21	2.50	5.65
22	2.40	5.90
23	3.30	5.60
24	3.20	4.40
25	1.70	5.90
26	1.50	6.20
27	2.80	7.50
28	2.50	8.70
29	2.80	7.00
30	3.30	7.20
31	3.50	7.00
32	3.60	6.50
33	2.90	7.00
34	3.80	7.40
35	2.10	4.50
Average	2.84	6.30
Standard Deviation	0.66	1.33

Supplementary Table 3 The table shows the multiple trails (Open Circuit Voltages) for PE Foam sheet using single and 3 PZTs connected in series.

PE FOAM	VO (V)	VO (V) – 3 PZT
1	3.00	9.50
2	5.00	7.50
3	4.20	7.00
4	3.80	8.00
5	3.20	8.40
6	3.00	8.90
7	4.50	12.00
8	4.80	7.00
9	5.50	11.50
10	5.80	12.50
11	6.20	13.00
12	3.30	9.80
13	2.50	7.50
14	3.20	7.70
15	3.30	6.50
16	3.40	9.70
17	2.90	11.00
18	5.20	10.00
19	4.80	10.50
20	4.00	7.20
21	4.10	6.90
22	5.40	6.50
23	3.70	13.20
24	4.80	8.50
25	5.50	8.40
26	5.60	7.60
27	3.50	7.50
28	3.80	6.90
29	3.90	7.00
30	3.70	7.20
31	6.20	7.00
32	2.90	6.50
33	3.30	6.50
34	3.50	7.00
35	3.00	7.10
Average	4.13	8.54
Standard Deviation	1.05	2.02

Supplementary Table 4 The table shows the multiple trails (Open Circuit Voltages) for PETG sheet using single and 3 PZTs connected in series.

PETG	VO (V) – Single PZT	VO (V) – 3 PZT
1	3.50	11.50
2	4.00	10.00
3	5.20	9.00
4	4.20	10.00
5	6.40	8.40
6	4.00	8.90
7	6.00	14.00
8	4.00	8.00
9	5.50	12.00
10	5.10	14.00
11	6.10	13.00
12	4.00	9.80
13	4.20	10.50
14	3.80	8.70
15	3.70	9.70
16	3.50	12.70
17	3.00	13.00
18	4.10	16.00
19	3.20	13.10
20	4.20	9.40
21	4.30	9.00
22	4.80	9.90
23	3.80	10.70
24	3.90	10.90
25	4.20	7.50
26	4.40	10.90
27	3.10	13.50
28	6.40	14.20
29	4.10	7.00
30	3.70	11.20
31	3.30	9.50
32	3.50	7.90
33	3.70	8.90
34	3.90	9.00
35	3.40	8.80
Average	4.23	10.59
Standard Deviation	0.91	2.21

Supplementary Table 5 The table shows the multiple trails (Open Circuit Voltages) for Gyroid 10% using single and 3 PZTs connected in series

Gyroid 10%	VO (V)	VO (V) – 3 PZT
1	7.00	7.50
2	5.00	9.20
3	6.00	10.40
4	5.30	8.90
5	4.80	11.30
6	5.80	7.80
7	6.00	12.10
8	6.80	9.60
9	8.80	8.70
10	8.00	10.90
11	7.50	9.50
12	5.50	11.50
13	9.00	12.00
14	5.50	12.50
15	8.50	10.00
16	6.00	10.60
17	6.40	12.00
18	6.80	13.50
19	6.50	12.70
20	6.80	13.00
21	7.00	10.20
22	6.80	14.50
23	5.50	14.20
24	7.20	14.20
25	8.00	13.50
26	7.50	13.50
27	8.50	13.20
28	8.40	9.80
29	8.20	10.80
30	7.50	10.00
31	7.50	9.20
32	5.80	9.40
33	7.00	10.00
34	8.50	8.80
35	8.20	9.00
Average	6.96	10.97
Standard Deviation	1.18	1.95

Supplementary Table 6 The table shows the multiple trails (Open Circuit Voltages) for Gyroid 20% using single and 3 PZTs connected in series.

Gyroid 20%	VO (V)	VO (V) – 3 PZT
1	6.00	6.90
2	5.20	9.50
3	5.00	7.80
4	5.80	8.20
5	6.00	10.10
6	6.50	9.30
7	7.80	13.40
8	7.00	11.30
9	7.40	10.00
10	7.60	14.00
11	5.20	13.50
12	5.40	13.50
13	6.50	14.20
14	5.80	13.00
15	5.00	13.20
16	7.00	12.40
17	7.60	9.50
18	5.80	8.50
19	6.50	9.90
20	6.50	8.80
21	7.50	12.20
22	6.50	10.80
23	6.00	9.50
24	6.00	8.80
25	5.50	13.00
26	7.00	10.50
27	6.80	7.50
28	6.80	8.50
29	5.00	8.70
30	5.80	10.00
31	6.80	10.20
32	6.60	9.80
33	6.80	8.20
34	6.00	9.80
35	6.80	12.00
Average	6.33	10.47
Standard Deviation	0.80	2.06

Supplementary Table 7 The table shows the multiple trails (Open Circuit Voltages) for Gyroid 30% using single and 3 PZTs connected in series.

Gyroid 30%	VO (V)	VO (V) – 3 PZT
1	6.00	5.90
2	5.00	7.30
3	4.6	9.50
4	4.4	6.20
5	4.80	11.10
6	6.20	10.40
7	6.00	8.70
8	4.50	12.30
9	3.20	7.80
10	3.60	10.60
11	3.80	8.90
12	4.80	5.40
13	4.50	6.80
14	5.50	9.20
15	5.80	11.50
16	6.00	10.00
17	4.20	9.50
18	4.50	10.6
19	5.00	8.50
0	5.20	8.90
21	4.00	9.50
22	4.40	9.20
23	4.50	10.00
24	5.80	9.00
25	5.20	6.50
26	6.20	6.20
27	6.00	6.80
28	6.00	7.20
29	6.00	7.50
30	5.00	8.50
31	5.00	9.50
32	5.80	7.10
33	5.20	6.90
34	3.40	8.00
35	3.60	9.50
Average	4.99	8.59
Standard Deviation	0.89	1.71

Supplementary Table 8 The table shows the multiple trails (Open Circuit Voltages) for Honeycomb10% using single and 3 PZTs connected in series.

Honeycomb 10%		VO (V)	VO (V) – 3 PZT
1		7.6	7.80
2		7.2	13.40
3		8.5	12.90
4		7.8	9.10
5		8.00	15.20
6		8.00	10.70
7		12.00	16.30
8		8.00	11.90
9		10.00	18.50
10		9.60	17.40
11		10.00	14.20
12		11.00	8.30
13		6.50	11.70
14		7.80	11.70
15		8.00	13.50
16		8.20	13.80
17		9.20	11.50
18		8.00	12.60
19		7.70	13.10
20		7.60	12.90
21		8.80	11.50
22		8.60	10.50
23		4.50	10.80
24		5.50	10.60
25		5.80	9.50
26		5.60	9.00
27		6.00	8.50
28		7.20	14.50
29		7.00	15.50
30		5.00	15.20
31		5.00	14.50
32		5.80	15.50
33		5.20	11.40
34		6.80	11.00
35		6.20	12.20
Average		7.50	12.48
Standard Deviation		1.85	2.61

Supplementary Table 9 The table shows the multiple trails (Open Circuit Voltages) for Honeycomb 20% using single and 3 PZTs connected in series.

Honeycomb 20%	VO (V)	VO (V) – 3 PZT
1	5.4	9.20
2	7	10.70
3	6.6	12.50
4	8	7.90
5	8.00	14.10
6	7.00	15.60
7	10.50	8.30
8	7.00	13.40
9	7.50	11.20
10	6.60	16.40
11	6.00	9.60
12	10.50	9.00
13	5.50	9.60
14	6.00	6.90
15	7.50	7.00
16	7.50	9.80
17	8.20	7.60
18	8.00	10.90
19	6.70	13.50
20	6.60	13.00
21	6.00	14.20
22	7.20	7.20
23	4.50	7.50
24	5.50	10.50
25	5.80	10.20
26	5.60	9.50
27	6.00	14.00
28	7.20	14.80
29	6.00	9.50
30	5.00	13.50
31	6.50	13.40
32	4.20	13.80
33	4.40	11.00
34	4.20	11.50
35	4.00	10.00
Average	6.49	11.05
Standard Deviation	1.59	2.65

Supplementary Table 10 The table shows the multiple trails (Open Circuit Voltages) for Honeycomb 30% using single and 3 PZTs connected in series.

Honeycomb 30%	VO (V)	VO (V) – 3 PZT
1	8	7.30
2	5.5	9.80
3	6	10.50
4	5	6.90
5	6.00	12.20
6	5.80	11.40
7	9.80	8.70
8	5.50	13.10
9	5.80	10.90
10	6.60	14.60
11	6.00	9.10
12	6.40	7.70
13	5.50	8.40
14	5.60	12.50
15	7.50	11.90
16	7.50	10.50
17	8.60	10.40
18	7.50	10.20
19	6.70	9.80
20	7.00	9.60
21	6.80	9.40
22	6.00	9.00
23	5.50	8.00
24	5.00	8.80
25	5.20	9.50
26	4.80	10.50
27	5.00	7.50
28	6.40	10.60
29	6.00	7.80
30	5.00	7.20
31	6.50	13.00
32	4.20	13.40
33	4.80	13.80
34	4.80	13.50
35	4.60	10.00
Average	6.08	10.21
Standard Deviation	1.22	2.09

Supplementary Table 11 The table shows the multiple trails (Open Circuit Voltages) for Rectilinear 10% using single and 3 PZTs connected in series.

Rectilinear 10%	VO (V)	VO (V) – 3 PZT
1	7.00	8.10
2	9.00	12.50
3	7.5	10.70
4	5.3	9.30
5	8.00	15.20
6	8.60	11.90
7	8.60	14.80
8	10.50	16.30
9	5.80	13.50
10	7.40	13.40
11	6.90	10.20
12	6.40	12.80
13	5.50	8.90
14	5.60	16.50
15	8.80	14.10
16	8.10	13.50
17	8.60	11.00
18	7.50	14.50
19	6.70	9.50
20	7.00	8.50
21	6.80	7.70
22	6.00	9.50
23	5.50	7.50
24	5.00	10.50
25	5.20	12.50
26	4.80	14.00
27	8.60	9.50
28	7.20	8.80
29	7.40	8.20
30	7.20	7.60
31	6.50	6.90
32	9.80	12.90
33	9.50	11.20
34	7.80	12.00
35	6.60	13.00
Average	7.27	11.34
Standard Deviation	1.44	2.69

Supplementary Table 12 The table shows the multiple trails (Open Circuit Voltages) for Rectilinear 20% using single and 3 PZTs connected in series.

Rectilinear 20%	VO (V)	VO (V) – 3 PZT
1	6.5	7.20
2	8	9.10
3	6.5	10.50
4	4.6	6.80
5	6.00	11.30
6	6.60	12.90
7	6.40	7.50
8	8.00	8.00
9	9.00	8.20
10	9.20	15.60
11	5.50	10.80
12	5.80	9.50
13	4.50	7.50
14	4.20	7.00
15	5.00	8.30
16	5.20	8.00
17	5.20	8.70
18	6.80	13.20
19	6.20	9.40
20	6.00	6.50
21	5.80	6.80
22	8.10	12.00
23	8.20	11.50
24	8.00	13.00
25	4.80	9.00
26	4.80	7.90
27	8.60	14.10
28	5.80	16.50
29	5.00	9.50
30	5.20	10.50
31	6.20	11.00
32	7.40	11.80
33	7.00	12.00
34	7.80	9.50
35	7.50	10.00
Average	6.45	10.03
Standard Deviation	1.41	2.55

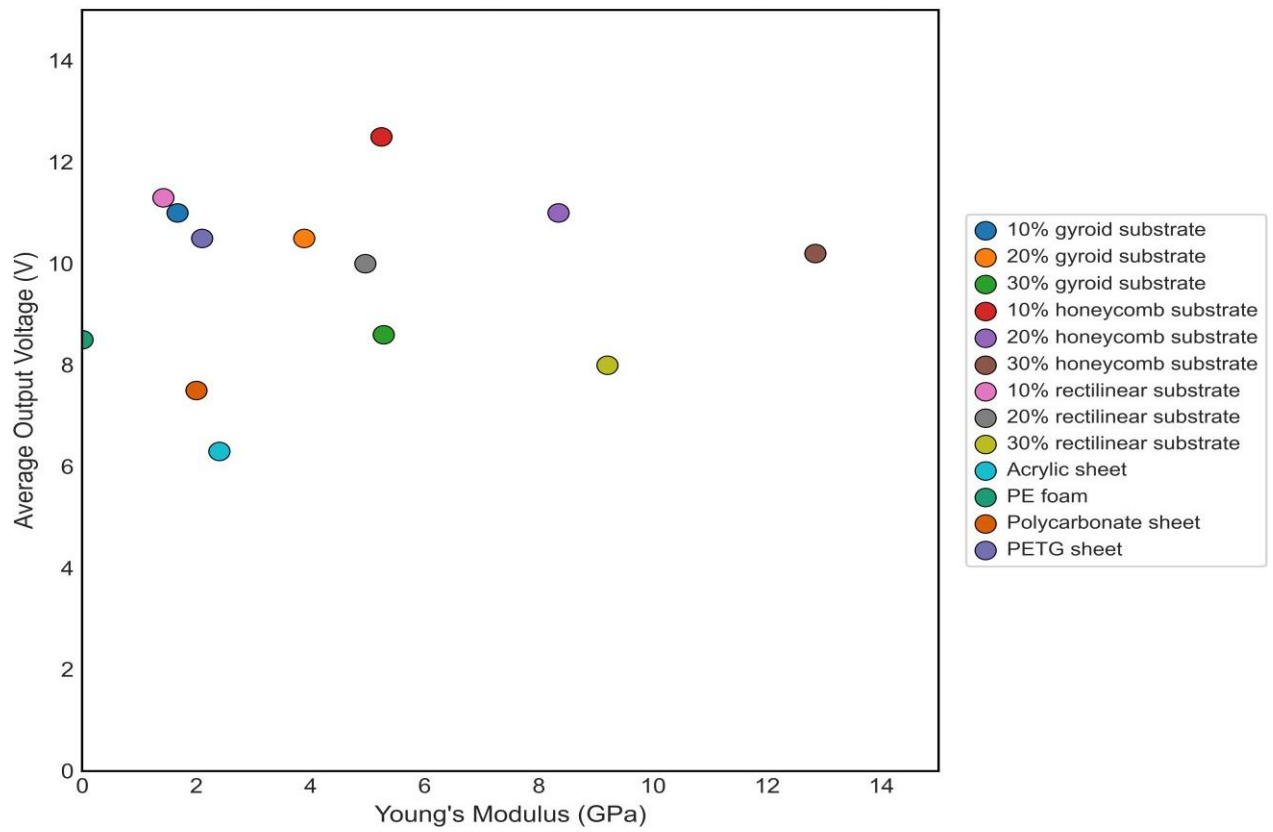
Supplementary Table 13 The table shows the multiple trails (Open Circuit Voltages) for Rectilinear 30% using single and 3 PZTs connected in series.

Rectilinear 30%	VO (V)	VO (V) – 3 PZT
1	5.00	6.50
2	5.3	7.50
3	4.5	9.20
4	4.2	5.90
5	5.00	10.60
6	5.20	8.40
7	5.20	7.30
8	3.50	6.80
9	4.50	9.20
10	4.10	10.40
11	3.50	8.50
12	7.50	8.20
13	4.50	6.50
14	4.20	7.70
15	5.00	8.80
16	4.60	8.80
17	4.00	8.00
18	3.80	8.00
19	3.50	7.10
20	3.50	5.70
21	4.20	7.00
22	4.50	7.50
23	5.20	7.20
24	5.00	9.50
25	4.20	9.20
26	3.80	9.00
27	4.00	11.20
28	4.10	8.90
29	4.50	6.50
30	3.50	6.30
31	3.50	6.80
32	6.10	6.00
33	5.20	7.20
34	5.40	8.50
35	6.00	9.50
Average	4.56	7.98
Standard Deviation	0.91	1.39

Supplementary Note 1: Relationship Between Young's Modulus and Output Voltage

Overall, there is a clear relationship between waveform characteristics such as open circuited voltages and the base layer flexibility (Young Modulus), as demonstrated via the voltage outputs. Firstly, the more flexible base layers—PETG, PE foam, and the meta-materials (3D printed structures)—showed more distinct waveforms with larger peak-to-peak voltages (V_{pk-pk}), larger amplitudes (V_o) and greater root mean square voltages (V_{rms}). Greater PZT displacement during mechanical loading is made possible by flexible base layers, and this increases the strain that the piezoelectric material experiences, which increases voltage generation.

The Young's Modulus of the substrate played the crucial role in optimizing the harvested energy. As looking at the scatter plot, the lower the young modulus the higher the voltages, the lower moduli allowed the greater and uniform stress distribution across the floor tiles. This study highlighted the importance of selecting the low moduli base layers for the PZT harvesting tiles without complicating the whole structure.



Supplementary Figure 1: Plot of average output voltage versus elastic modulus