

Performance enhancement of PZT material for circular diaphragm energy harvester

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Abstract The property of piezoelectric material was one of the keys to optimize energy harvester based on piezoelectric effect. In this paper, the relation between the parameters of piezoelectric material and the performance of circular diaphragm energy harvester was studied. Theoretical analysis and idiographic experiment were combined to estimate the dependence of output power on the material parameters: piezoelectric coefficient d_{33} and dielectric constant ϵ . The results show piezoelectric material with high- d_{33} and low- ϵ was good for increasing the output power of energy harvester, and the influence of piezoelectric coefficient is more obvious than that of dielectric constant. Among soft PZT, material PZT-51 could best fit energy harvesting. By optimizing PZT material, the energy harvester using single piezoelectric circular diaphragm could generate a maximum power of 9.08 mW for a matching load about 45 k Ω and a tip mass of 30 μ g at its resonant frequency of 178 Hz.

1 Introduction

With the development of ultra low power microelectronic devices, the demand for utilization of environmental energy is increasing rapidly [1–4]. There are various available green energy in the environment, such as light, wind, thermal

gradient and mechanical energy. Energy harvesting technology based on solar, wind etc. is well studied, and more attentions are attracted on energy generating from mechanical vibration. There are three methods which can transfer mechanical vibration to electric energy: electromagnetic, electrostatic, and piezoelectric [5]. Compared with electromagnetic and electrostatic methods, piezoelectric energy harvesting has many advantages, such as free external power source, high power density, practical convenience for application, and accessibility to be fabricated at different scales: macro, micro, and nano-scale [6–8].

The improvement of piezoelectric energy harvesting is mainly derived from three aspects: the structure of piezoelectric energy harvester, external circuit and the properties of piezoelectric materials. There is a great effect on the performance of harvester as the change of structure such as cantilever and cymbal, a multilayered cantilever structure with a Si proof mass is designed by Park et al. [9] to harvest a lower lever vibration energy. Daniels et al. [10] analyzed piezoelectric cymbal transducer for non-resonant energy harvesting in their research. For external circuit, the traditional energy harvester circuit consists of two components: a rectifier and a filter. Do et al. [11] proposed a new high efficiency piezoelectric energy harvesting circuit with two synchronized switches.

Just like the structure and external circuit, piezoelectric material also has a great impact on energy harvesting efficiency [12, 13]. Table 1 compared the performance parameters of some common piezoelectric materials for energy harvesting application. It is obvious that the piezoelectric coefficient d_{33} of PMN-PT single crystal is significantly higher than that of other materials. PMN-PT is famous for extremely high energy density and energy conversion efficiency. For PVDF copolymer, its advantages are high mechanical strength and chemical stability.

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Table 1 Performance parameters for common piezoelectric materials for energy harvester

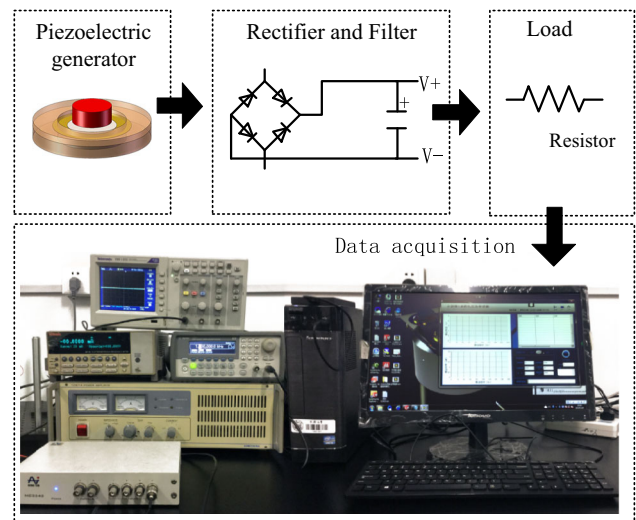
	PMN-PT single crystal	PVDF copolymer	KNN	PZT
d_{33} (pC/N)	2000–3500	35–	200–	400–
ϵ	5500–6500	13–	500–1000	2000–
$\tan \delta$	0.008–0.01	0.07–	0.02–	0.01–0.03
T_c (°C)	130–	110–	400–	270–

However, the synthesis of lager-volume single crystal and copolymer is difficult and will cost more. KNN-based lead-free piezoelectric ceramic material, which is characterized by environmental protection and harmlessness, can be used in a lager temperature range because of its high T_c . And PZT piezoceramic actuator exhibits remarkable properties such as high resolution, quick response, suitable piezoelectric parameters, and it is widely used. Specially, PZT material is cheap, easily available and can be fabricated in small size, which is significant in application of low frequency transducer. There are many researches about piezoelectric energy harvesting based on various piezoelectric materials. Song et al. [14] compared monolithic and composite piezoelectric material-based energy harvesting devices. Neiss and Goldschmidtboeing [15] discussed the different performance between soft PZT and hard PZT. And Mukherjee and Datta [16] studied the effect of parameters characterizing piezoelectric material's properties using finite element analysis. Most of the researches on piezoelectric material energy harvesting are concerned with macroscopic materials or finite element analysis. Material parameters analysis is almost based on theory instead of experiment results.

In this paper, the relationship between piezoelectric material parameters and the output power will be investigated by experimental and theoretical studying. Piezoelectric circular diaphragm is applied in the study because of convenience to be fabricated and vast perspectives. Furthermore, this paper focuses on the effect of piezoelectric coefficient d_{33} and dielectric constant ϵ on the output power. In order to discuss their relationship straightforward, other factors is fixed in all the studies by using one set of experimental apparatus and same-sized piezoelectric materials at their optimal resistive load.

2 Theoretical analysis

The structure of harvester studied in this paper consists of a piezoelectric circular diaphragm oscillator, harvesting circuit, and data acquisition devices. As shown in Fig. 1, piezoelectric generator convert mechanical vibration into electric energy; harvesting circuit act as rectifier and filter to process electricity; load resistor is chosen to consumer the electricity; and data acquisition devices collect relevant

**Fig. 1** System of piezoelectric energy harvester

data. The output power is selected as standard to evaluate the performance of piezoelectric energy harvester.

Suppose the influence of clamp and measuring apparatus can be ignored, further suppose there is no electromechanical dissipation in this system. In this case, an equivalent formula for the single piezoelectric oscillator is shown as follows.

Piezoelectric equation:

$$D = d_{33} \cdot T \quad (1)$$

where D is electric displacement, d_{33} is the piezoelectric coefficient, and T is the stress distributed on the piezoelectric material. So the relation between Q and F can be derived as:

$$Q = d_{33} \cdot F \quad (2)$$

where Q is electric quantity and F is application force.

On the other hand, the capacitance is shown as:

$$C = \epsilon \cdot A / \delta \quad (3)$$

where C is capacitance, ϵ is dielectric constant, A is the area of piezoelectric element, and δ is material thickness.

With Eqs. (2) and (3), we can define the output voltage as:

$$V = d_{33} \cdot F \cdot \delta / (\epsilon \cdot A) \quad (4)$$

For output current, the equation shows as:

$$I = dQ/dt = d_{33} \cdot F \cdot f \tag{5}$$

where f represents resonant frequency. Therefore, the output power which is used to evaluate the performance of piezoelectric system can be described as:

$$P = V \cdot I = d_{33}^2 \cdot F^2 \cdot f \cdot \delta / (\epsilon \cdot A) \tag{6}$$

Given Eq. (6) is derived out based upon the hypothesis of ideal condition, it can't give a quantitative description, but it can explain piezoelectric material parameters' effect on output power qualitatively.

3 Experiments and result discussion

In this study, sample 1–6 (abbreviated as S1–S6) are all PZT-5H material before processing. Table 2 summarizes the performance parameters for these samples. In order to know the effect of single factor d_{33} (piezoelectric coefficient) on output power, S1–S5 are dealt with specially. To begin with, the first five samples are depolarized through high sintering. For the second step, samples are polarized under the condition of certain polarization temperature polarization voltage and polarization time. Through changing polarization voltage and time, each sample has different piezoelectric coefficient. And finally, all the samples are glued to copper sheet for piezoelectric vibrator.

The dielectric constant of original sample is about 2400. Figure 2 shows the dielectric constant of S1–S5 as a function of measuring frequency. As shown, there is no change for the dielectric constant of all piezoelectric material after processing, same as the original material S6. Therefore, the performance parameters of all samples are summarized in Table 3. It is obvious that all parameters are the same because they are the same material originally, expect the piezoelectric coefficient d_{33} .

As known, in the case of impedance and resonant frequency, piezoelectric oscillator work in the best state, generating maximum power. Deviating from the resonant frequency or not under the matching impedance, the output power will reduce significantly. Besides, with the change of vibration frequency the impedance of piezoelectric material are different. Figure 3 shows the matching

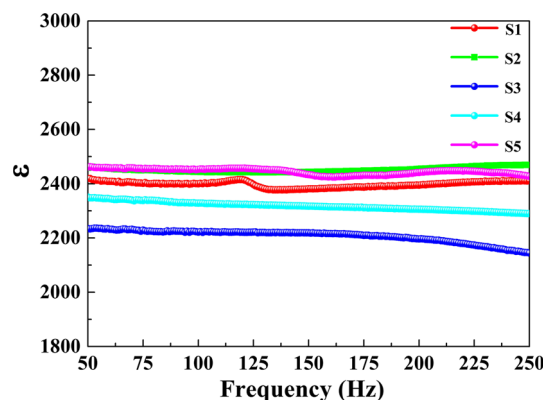


Fig. 2 Dielectric constant versus measuring frequency for energy harvester with different piezoelectric samples

impedance of energy generator as a function of excitation frequency. Based on Fig. 3, each sample's matching impedance under its resonant frequency can be obtained to guarantee the maximum output power.

As shown in Fig. 4, the output power as a function of the excitation frequency and different-piezoelectric coefficient sample is measured by connecting the circular diaphragm energy harvester with its optimal load resistor. From this figure, it can be seen that the location of each sample's resonant peak is about 170 Hz and the measurement error is in the extent permitted. This is due to both material and copper sheet size are the same and one structure is used in each testing. As the piezoelectric coefficient increases from 40 to 400 pC/N, the maximum power improves significantly, shifting from 0.008 to 5.2 mW. The piezoelectric coefficient has a positive effect on output power, which is accord with the Eq. (6).

In addition, other two set of experiments about dielectric constant ϵ is studied in this paper. PZT-A–C are nearly same material expect having different dielectric constant. PZT-a–c also differ from each other in dielectric constant. PZT-A and PZT-a have different piezoelectric coefficient d_{33} .

Figure 5 illustrates the dielectric constant of material as a function of measuring frequency. It is obvious that PZT-A and PZT-a have similar dielectric constant about 2600, PZT-B and PZT-b have similar dielectric constant about 1900, and PZT-C has dielectric constant about 1500 similar with PZT-c.

Table 2 Performance parameters for the original material samples

Factors	Piezoelectric coefficient d_{33} (pC/N)	Dielectric constant (ϵ)	Mechanical quality factor (Qm)	Electromechanical coupling factor (kp)	$\tan \delta$	T_c (°C)
Samples	400	2400	76.3	0.734	0.02	300

Table 3 Performance parameters for different piezoelectric material samples

Sample	Material thickness (mm)	Material diameter (mm)	Dielectric constant ϵ	Piezoelectric coefficient before processing (pC/N)	Piezoelectric coefficient during processing (pC/N)	Piezoelectric coefficient after processing (pC/N)
S1	0.25	25	2400	400	0	40
S2	0.25	25	2400	400	0	90
S3	0.25	25	2400	400	0	200
S4	0.25	25	2400	400	0	270
S5	0.25	25	2400	400	0	330
S6	0.25	25	2400	400	400	400

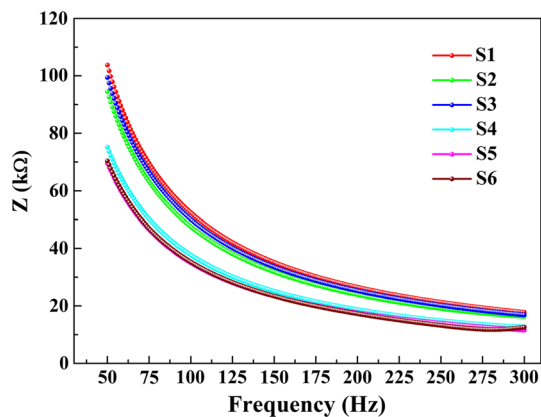
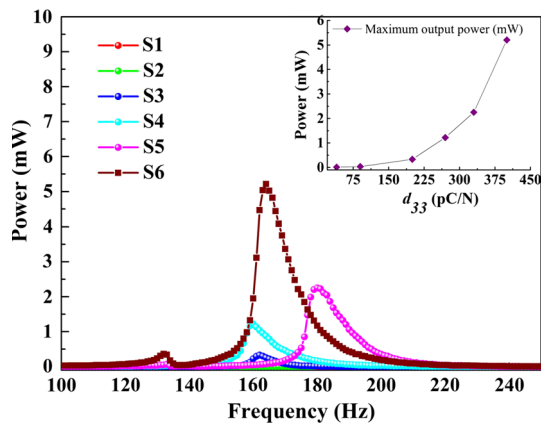
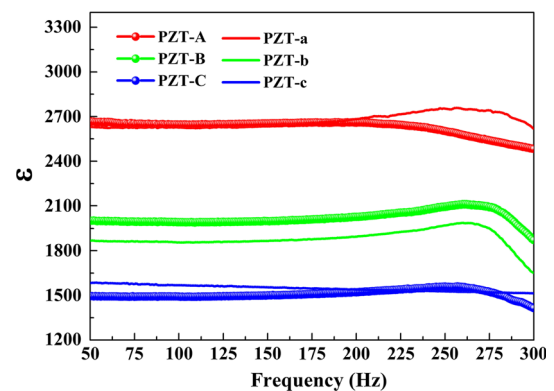
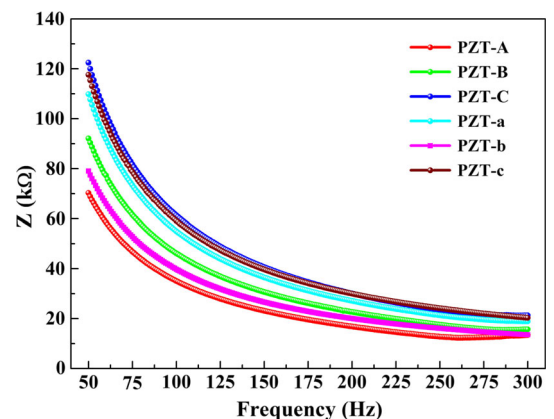
**Fig. 3** Matching impedance versus measuring frequency for energy harvester with different piezoelectric samples**Fig. 4** Power output versus measuring frequency for energy harvester with different piezoelectric coefficient samples under their optimal load resistor in a single structure

Figure 6 reveals the relation between exciting frequency and matching impedance. Figure 7a, b show two type of samples' output power as a function of measuring frequency and different- ϵ material respectively. As the dielectric

**Fig. 5** Dielectric constant versus measuring frequency for energy harvester with different piezoelectric samples**Fig. 6** Matching impedance versus measuring frequency for energy harvester with different piezoelectric samples

constant decreases from 2600 to 1500, the maximum output power increases obviously.

Table 4 summarizes the specific data about the effect of dielectric constant on output power. By observing, it is evident that no matter the piezoelectric coefficient is high or low, the decrease of the dielectric constant can lead

Fig. 7 a Power output versus measuring frequency for energy harvester with PZT-A–C under their optimal load resistor in a single structure. **b** Power output versus measuring frequency for energy harvester with PZT-a–c under their optimal load resistor in a single structure

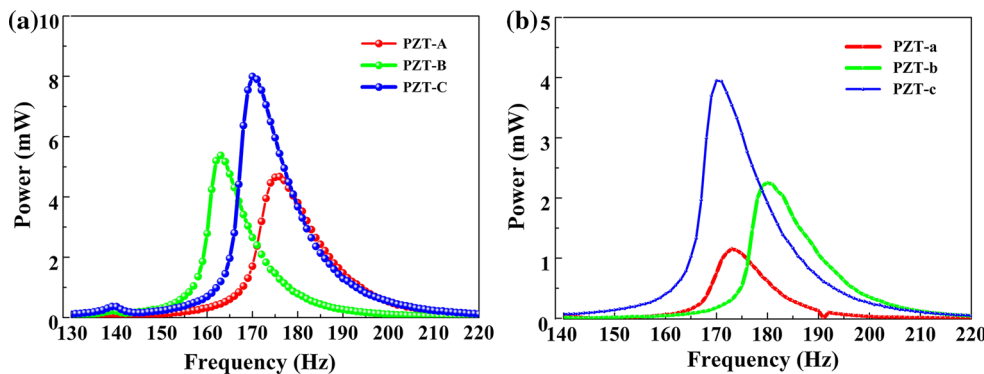


Table 4 Power output with matching load resistor under its resonant frequency for different piezoelectric material samples

Sample	Piezoelectric coefficient $d_{33} = 420$ (pC/N)			Piezoelectric coefficient $d_{33} = 330$ (pC/N)		
	PZT-A	PZT-B	PZT-C	PZT-a	PZT-b	PZT-c
Dielectric constant (ϵ)	2600	1900	1500	2600	1900	1500
Resonant frequency (Hz)	176	163	170	173	180	170
Matching load resistor (k Ω)	19	28	36	31	22	35
Maximum power (mW)	4.67	5.37	7.99	1.16	2.25	3.95

higher output power. This result can be explained by Eq. (6). And compared with piezoelectric coefficient, material dielectric constant need change more to realize the increase of power because from Eq. (6) the power is proportional to d_{33}^2 and is inversely proportional to ϵ in an ideal case. In addition, data in Table 2 shows that when material has high piezoelectric coefficient about 420 pC/N and low dielectric constant about 1500, the maximum power of single piezoelectric circular diaphragm harvester with 30 g tip mass can almost reach 8 mW.

Three types of lead zirconate titanate (PZT-53, PZT-5H, PZT-51) are chosen to investigate the dependence of the output power on the properties of materials. All geometric parameters of material and structure are kept the same. Figure 8 shows the output power of harvester using various materials as a function of excitation frequency under their matching load resistor. Moreover, material parameters and detailed data about generator performance are summarized in Table 5. From the table, it can be seen that among soft PZT series, PZT-51 best fits energy harvesting for its highest output power. Difference in Q_m , k_p among three materials is negligible. Though the d_{33} of PZT-53 is lower, harvester using PZT-53 can get fine output power of 5.66 mW because its ϵ is extremely low. PZT-5H has the highest d_{33} , but its ϵ is higher, so the output power after equalization is 6.37 mW. And output power of harvester using PZT-51 can reach 9.08 mW because material PZT-51 has good characters of higher d and lower ϵ .

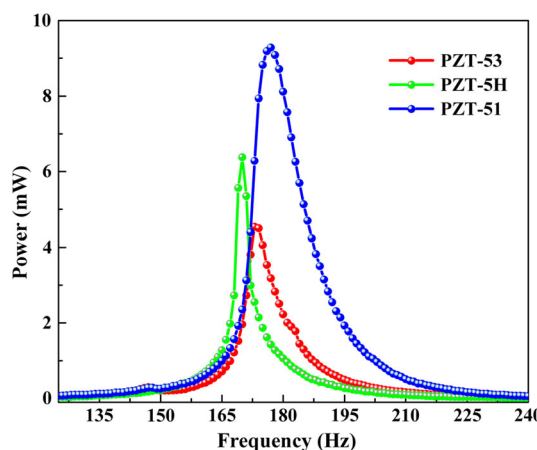


Fig. 8 Power output versus measuring frequency for energy harvester with soft PZT series under their optimal load resistor

4 Conclusion

Piezoelectric materials are prepared to investigate the effect of measuring frequency and material parameters on output power of circular diaphragm energy harvester. As piezoelectric coefficient increases and dielectric constant decreases, the output power improves obviously. And piezoelectric coefficient has a stronger impact on output power compared with dielectric constant. Besides, material PZT-51 best fits energy harvesting among soft PZT series,

Table 5 Material parameters and power output with matching load resistor under its resonant frequency for soft PZT series

Material	Mechanical quality factor (Q _m)	Electromechanical coupling factor (k _p)	Piezoelectric coefficient d_{33} (pC/N)	Dielectric constant (ϵ)	Resonant frequency (Hz)	Matching load resistor (k Ω)	Maximum power (mW)
PZT-53	44.09	0.631	250	440	173	122	4.54
PZT-5H	75.3	0.732	430	2600	170	20	6.37
PZT-51	41.6	0.722	380	1150	178	45	9.08

the maximum power for a single circular diaphragm energy oscillator can reach over 9 mW with the matching load under its resonant frequency when material PZT-51 is used. Our results provide a method for optimizing piezoelectric energy system, which lay a foundation for further research of energy harvesting and low power.

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References

- J. Schonberger, R. Duke, S.D. Round, *IEEE Trans. Ind. Electron.* **53**, 1453 (2006)
- M.E. Kiziroglou, C.R. He, E.M. Yeatman, *IEEE Trans. Ind. Electron.* **56**, 1101 (2009)
- Z. Xiao, T.Q. Yang, Y. Dong, X.C. Wang, *Appl. Phys. Lett.* **104**, 223904 (2014)
- P.D. Mitcheson, E.M. Yeatman, G.K. Rao, A.S. Holmes, T.C. Green, *Proc. IEEE* **96**, 1457 (2008)
- P.D. Mitcheson, T.C. Green, E.M. Yeatman, *Microsyst. Technol.* **13**, 1629 (2007)
- W.G. Ali, G. Nagib, In *2012 International Conference on Engineering and Technology (ICET)* (2012). doi:[10.1109/ICEngTech.nol.2012.6396115](https://doi.org/10.1109/ICEngTech.nol.2012.6396115)
- P.D. Mitcheson, E.K. Reilly, T. Toh, P.K. Wright, E.M. Yeatman, *J. Micromech. Microeng.* **17**, S211 (2007)
- R. Torah, P. Glynne-Jones, M. Tudor, T.O. Donnell, S. Roy, S. Beeby, *Meas. Sci. Technol.* **19**, 125202 (2008)
- J.C. Park, J.Y. Park, Y.P. Lee, *J. Microelectromech. Syst.* **19**, 1215 (2010)
- A. Daniels, A. Giuliano, M.L. Zhu, A. Tiwari, *GreenCom-iThings-CPSC 1665* (2013). doi:[10.1109/GreenCom-iThings-CPSCom.2013.303](https://doi.org/10.1109/GreenCom-iThings-CPSCom.2013.303)
- X.D. Do, C.J. Jeong, H.H. Nguyen, S. K. Han, S.G. Lee, In *2011 International SOC Design Conference (ISOCC)* (2011). doi:[10.1109/ISOCC.2011.6138792](https://doi.org/10.1109/ISOCC.2011.6138792)
- F.L. Zhu, J.H. Qiu, H.L. Ji, K.J. Zhu, *J. Mater. Sci. Mater. Electron.* **26**, 2897 (2015)
- B. Praveenkumar, H.H. Kumar, D.K. Kharat, *J. Mater. Sci. Mater. Electron.* **17**, 515 (2006)
- H.J. Song, Y.T. Choi, N.M. Wereley, A. Purekar, *J. Intell. Mater. Syst. Struct.* **25**, 1825 (2014)
- S. Neiss, F. Goldschmidtboeing, *J. Phys. Conf. Ser.* **476**, 01235 (2013)
- A. Mukherjee, U. Datta, In *2010 Annual IEEE India Conference (INDICON)* (2010). doi:[10.1109/INDCON.2010.5712611](https://doi.org/10.1109/INDCON.2010.5712611)