

# LOW-FREQUENCY ENERGY HARVESTING USING A LAMINATED PVDF CANTILEVER WITH A MAGNETIC MASS

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**Abstract:** This paper reports an experimental study of a polyvinylidene fluoride (PVDF) cantilever with a magnetic mass for piezoelectric and electromagnetic energy harvesting. Due to the low Young's modulus of PVDF and laminated polymer materials, an energy harvester with a low resonance frequency of 14 Hz is developed by attaching a NdFeB magnet with a mass of 0.95 g to the tip of the cantilever. By applying a vibration with a frequency of 14 Hz and acceleration of 0.92 G, the PVDF based energy harvester achieves a peak-to-peak output voltage of 32 V. A maximum power output of 16  $\mu$ W is obtained with an optimized load resistance of 6 M $\Omega$ . The output from the energy harvester is converted to a selectable DC voltage output of 1.8 V, 2.5 V, 3.3 V and 3.6 V using an energy harvesting IC. In addition, electromagnetic energy harvesting by locating a coil below the magnetic tip is also demonstrated.

**Keywords:** PVDF cantilever, energy harvesting, electromagnetic, piezoelectric

## INTRODUCTION

Electronic devices and micromachined sensing devices have shrunk in size and energy consumption to unprecedented levels of several microwatts. Vibration-driven energy harvesters are attracting more and more attentions as the power source to take the place of the micro-batteries in the field of wireless sensor network and health monitoring system [1]. Various transduction mechanisms such as electromagnetic, electrostatic, piezoelectric have been demonstrated for vibration-driven energy harvesters [2-4]. Energy harvesting from the human motion is one of the best solutions for wearable human monitoring devices. However, as the power density from the human motion are limited to a frequency range of less than 20 Hz, it is very important to design the vibration structure of the energy harvester resonating at this frequency range with a large bandwidth. For piezoelectric energy harvesters operated in the transverse piezoelectric mode, the maximum power generated by the mechanical vibration at resonance is given by  $P_{max}=k_{31}^2 m Q^2 A^2 / 4 \omega$ , where  $k_{31}$  is the electromechanical coupling coefficient,  $m$  is the mass of the resonator,  $Q$  is the mechanical quality factor of the resonator,  $A$  is the acceleration amplitude of the input vibrations, and  $\omega$  is the resonance frequency [5]. Compared to conventional piezoelectric materials such as PZT or AlN, polyvinylidene fluoride (PVDF) has a low Young's modulus and comparable electromechanical coupling factor [6-8] as shown in table 1. Though the  $Q$  factor of PVDF based devices is lower than that of piezoelectric ceramics, piezoelectric energy harvesters with low resonance frequencies can be fabricated using PVDF as the transduction material. In addition, compared to PZT, which has a maximum strain of

0.1%, PVDF energy harvesters can achieve a much larger vibration amplitude and higher energy density. As a result, it is considered as a good solution to use PVDF based power generators for scavenging mechanical energy at low frequencies. In this paper, we present the investigation of a PVDF based low-frequency energy harvester, which is assembled by using a laminated PVDF cantilever mounted with a tiny cubic magnet. This device can realize dual-mode energy harvesting based on piezoelectric and electromagnetic transduction mechanism, respectively.

Table 1: Comparison of piezoelectric coefficients and mechanical property of the representative material.

	PVDF	PZT	AlN
E (GPa)	6.9	90	345
$\epsilon/\epsilon_0$	6~13	200~1500	9.5
$d_{31}$ (pC/N)	-8	0.22	-2.65
$k_{31}$ (CV/Nm)	0.12	0.22~0.31	
$d_{33}$ (pC/N)	30~33	90~233	3.4~5.1
$k_{33}$ (CV/Nm)	0.16	0.49~0.67	0.21

The values vary in terms of additives, process conditions, and thickness.

## EXPERIMENT SETUP

In order to investigate the feasibility of PVDF for energy harvesting application, a PVDF cantilever mounted with a tiny cubic magnet is developed for energy harvesting experiment as shown in Fig. 1. The cantilever (from TOKYO SENSOR CO., Ltd.) is fabricated by laminating a 28  $\mu$ m-thick PVDF layer with a 125  $\mu$ m-thick polyester layer. A protective coating is employed to form the cantilever device. The length, width, and thickness of the cantilever are 25

mm, 16 mm, and 205  $\mu\text{m}$ , respectively. The capacitance of the sensor is 1.3 nF. The laminated PVDF cantilever is mounted with a tiny NdFeB magnet with a volume of 125  $\text{mm}^3$  and a mass of 0.95g. A coil with a turn number of 20 and a diameter of 13 mm is located 1 mm below the magnet for electromagnetic energy harvesting. The cantilever is fixed to a vibrator driven by a function generator and a power amplifier. The output from the energy harvester is monitored using an oscilloscope with an input impedance of 10  $\text{M}\Omega$ .

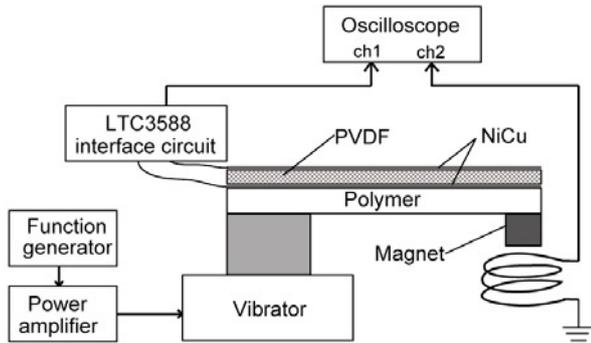


Fig. 1: Schematic diagram of the PVDF-based energy harvester and the measurement method.

## RESULTS AND DISCUSSIONS

Before the cantilever is mounted with the magnet for energy harvesting experiments, the mechanical property of the PVDF cantilever is evaluated by using a laser Doppler vibrometer (MLD-103A, NEOARK Corporation). The frequency response of the cantilever is measured as plotted in Fig. 2. The resonance frequency of the cantilever is 86 Hz and  $Q$ -factor is approximately 5.

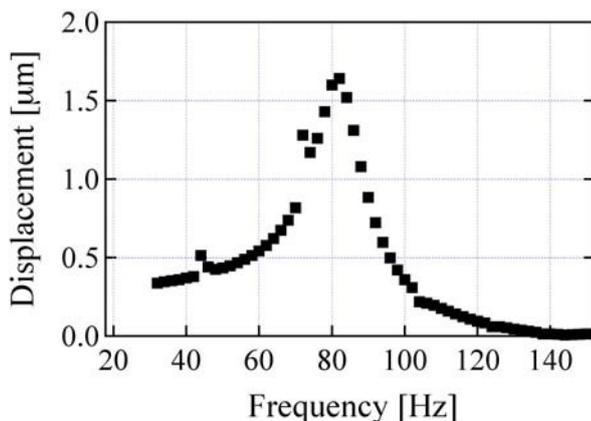


Fig. 2: Frequency response of the PVDF cantilever without magnet.

The resonance frequency of the PVDF cantilever decreases to 14 Hz by attaching the tiny cubic magnet. The energy harvesting experiment is carried out using the setup shown in Fig. 1. By applying a vibration source with an acceleration amplitude of 0.9 G at a

frequency of 14 Hz, the voltage output from the PVDF cantilever and coils with a resistance load of 10  $\text{M}\Omega$  are measured simultaneously as shown in Fig. 3. Compared to electromagnetic energy harvesting, much higher voltage output is achieved by the PVDF based piezoelectric energy harvester.

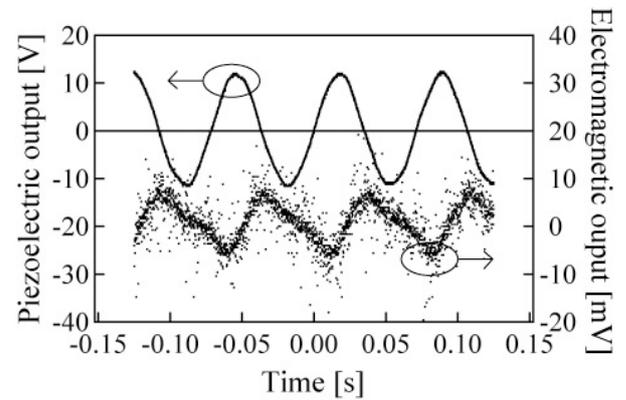


Fig. 3: Voltage output from the PVDF cantilever and coils with a resistance load of 10  $\text{M}\Omega$ , and an acceleration amplitude of 0.9 G at a frequency of 14 Hz.

The frequency response of the voltage output from piezoelectric and electromagnetic energy harvesting is measured. Figure 4 shows the voltage output of the PVDF energy harvester as a function of the frequency and amplitude of the vibration with a load resistance of 10  $\text{M}\Omega$ . A peak-to-peak output voltage of 32 V is achieved at the resonance frequency of 14 Hz with an acceleration amplitude of 0.92 G. Figure 5 illustrates the results of electromagnetic energy harvesting. The maximum peak-to-peak output voltage is limited to 15 mV at the resonance frequency of 14 Hz with an acceleration amplitude of 0.92 G. Though the voltage output from the electromagnetic energy harvesting method is small, with the consideration of low impedance of coils, a comparable power output can be achieved by optimizing the design of the coils and magnetic circuit in the future.

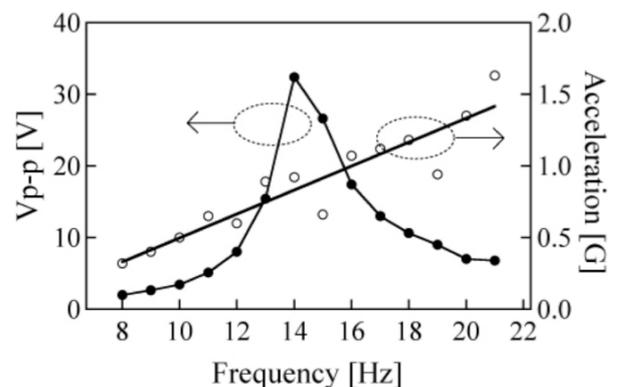


Fig. 4: Voltage output of the PVDF energy harvester as a function of the frequency and acceleration amplitude of the vibration source.

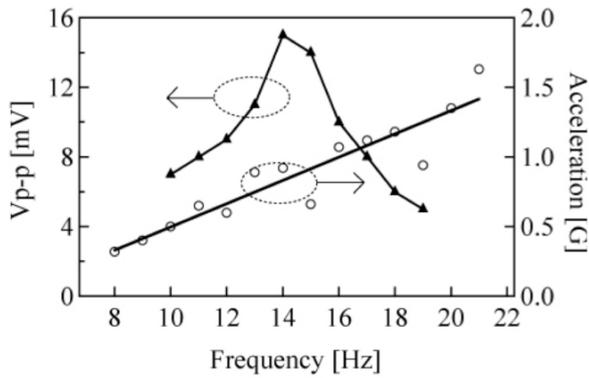


Fig. 5: Voltage output of the electromagnetic energy harvester as a function of the frequency and acceleration amplitude of the vibration source.

The voltage and power output of the PVDF energy harvester as a function of load resistance is plotted in Fig. 6, while the frequency and the acceleration amplitude of the vibration are 17 Hz and 1.2 G, respectively. The output voltage increases monotonously by increasing the load resistance. A maximum power output of 16  $\mu\text{W}$  is achieved with a load resistance of approximately 6  $\text{M}\Omega$ , which is equal to the electrical impedance of the PVDF device at the frequency of 17 Hz.

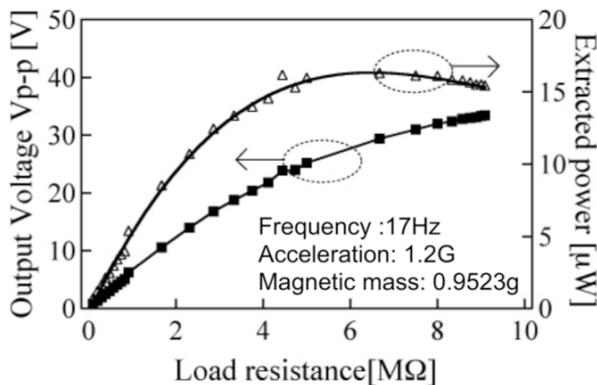


Fig. 6: Voltage and power output of the PVDF energy harvester as a function of load resistance while the frequency and amplitude of the vibration are 17Hz and 1.2 G, respectively.

A commercial piezoelectric energy harvesting power supply (LTC3588-1 from Linear Technology Corporation) is used for rectification and voltage regulation [9]. The LTC3588-1 integrates a low-loss full-wave bridge rectifier with a high efficiency buck converter optimized for high output impedance energy sources such as piezoelectric transducers. Four output voltages, 1.8V, 2.5V, 3.3V and 3.6V, are pin selectable with continuous output current. The energy harvesting circuit with LTC3588-1 is shown in Fig. 7. A storage capacitor of 10  $\mu\text{F}$  is used to accumulate charges until the buck converter can efficiently transfer a portion of

the stored charge to the output. The output voltage level is controlled by D0, D1 switches.

While the output of the circuit is connected with a load resistance of 1  $\text{M}\Omega$ , the output voltage from the PVDF energy harvester in a vibration source with an amplitude of 0.92 G and frequency of 14 Hz is rectified to a DC voltage of 1.5 V as shown in Fig. 8. However, selectable voltage output is not achieved and a large voltage fluctuation occurs due to the large power consumption compared to the scavenged energy. By increasing the load resistance to 10  $\text{M}\Omega$  to reduce the output current, selectable output voltages of 1.8 V and 3.2 V are achieved as illustrated in Fig. 9.

Using our experiment setup, the feasibility of dual-mode energy harvesting using a PVDF based piezoelectric resonator with an integrated tiny magnet is verified. PVDF based energy harvesters achieve an energy output of 16  $\mu\text{W}$  at low frequency of 17 Hz and acceleration amplitude of 1.2 G. This PVDF energy harvester will be used in the large model of human activity monitoring system as an assistant power supply, which was developed in our research group [10]. The next step is batch fabrication of the low-frequency PVDF based energy harvesters.

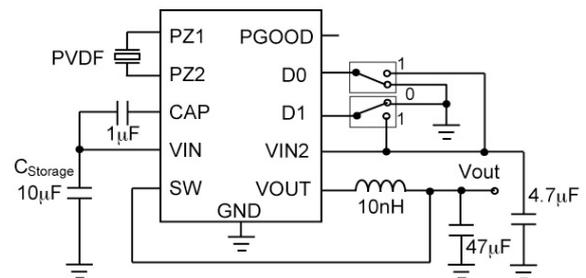


Fig. 7: Interface circuit for piezoelectric energy harvesting power supply using LTC3588-1.

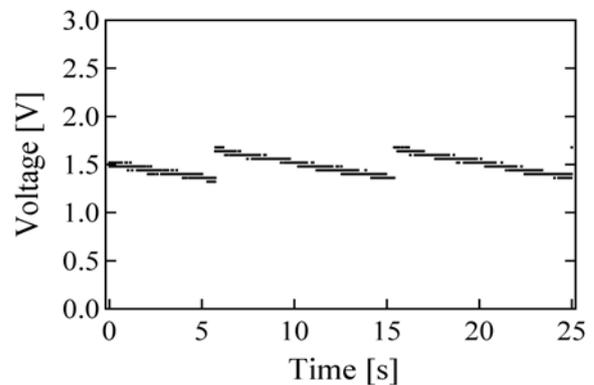


Fig 8: DC voltage output of the self-powered LTC3588 circuit using the energy from the PVDF energy harvester with a load resistance of 1  $\text{M}\Omega$ , while the frequency and amplitude of the vibration are 14 Hz and 0.92 G, respectively.

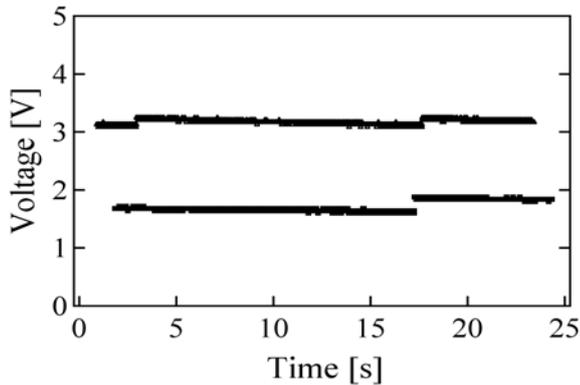


Fig. 9: Selectable DC voltage output of the self-powered LTC3588 circuit using the energy from the PVDF energy harvester with a load resistance of 10 M $\Omega$ , while the frequency and amplitude of the vibration are 14 Hz and 0.92 G, respectively.

## CONCLUSIONS

In summary, in order to scavenging low frequency mechanical energy from the human motion, a PVDF based energy harvester was developed. It consists of a commercial laminated PVDF cantilever with a mounted tiny magnet. At a low frequency of 14 Hz, A peak-to-peak output voltage of 32 V was achieved with an acceleration amplitude of 0.92 G. A maximum power output of 16  $\mu$ W was obtained with an optimal load resistance of 6 M $\Omega$ , while the frequency and amplitude of the vibration are 17 Hz and 1.2 G, respectively. The voltage rectification and regulation were performed using a commercial IC LTC3588-1, which is designed for piezoelectric energy harvesting. In addition, piezoelectric and electromagnetic dual-mode energy harvesting was demonstrated using our experiment setup. This device will be firstly used in our large model of human activity monitoring system.

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