Ferroelectret energy harvesting with 3D-printed air-spaced cantilever design

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Abstract
Vibrational energy harvesters of air-spaced cantilever design, utilizing ferroelectrets as the electroactive element, are a very recent concept. Such systems, based on the $d_{31}$ piezoelectric effect are further studied with harvesters of improved design, partially implemented by additive manufacturing. The focus of the present work is on the dependence of frequency response, resonance frequency, and generated power on the distance of the ferroelectret from the cantilever beam and on the pre-stressing of the ferroelectret. Experimental data are compared with both analytical and numerical evaluations. It is found that the power generated can be increased by one to two orders of magnitude by proper choice of distance. A suitable pre-stress yields another increase of power by a factor of 2 to 10 and linearizes the response. Thus, normalized output powers more than 1000 $\mu$W referred to an acceleration of 9.81 ms$^{-2}$ and a seismic mass of 3.5 g, can be achieved, which significantly exceeds previous results of cantilever-based energy harvesters.

KEYWORDS
air-spaced cantilever, energy harvesting, ferroelectret, piezoelectret, piezoelectric polymers

1 INTRODUCTION

Currently most mobile electronic devices use rechargeable batteries. Replacing or recharging those represents a challenging task in a number of applications[1-3] such as sensor networks used to monitor widely distributed production and process engineering plants, as well as embedded and implanted sensors for medical applications. In order to supply these electronic devices with energy in places where electric power is not readily available, energy harvesting systems have become a steadily growing alternative.

Energy harvesting is defined as the extraction of electrical energy from ambient sources such as heat, vibration or air currents for low power consumption devices[4-9]. Although energy harvesters have been investigated and even commercialized, more compact and efficient solutions are required.

In vibrational energy harvesting, piezoelectric transducers utilizing the direct piezoelectric effect have been
investigated for the last 20 years, where piezoceramics such as lead zirconate titanate (PZT) have been the dominating materials.[10–14] After the classification of lead as a toxic material, the restrictions to its use have been increased. This, in turn, offered the opportunity for research of new lead-free materials such as ferroelectric polymers represented dominantly by polyvinylidene fluoride (PVDF) and its copolymers.[15–17]

Other polymer categories that can be considered piezoelectric are the voided charged polymers, also called ferroelectrets or piezoelectrets.[18–21] In this paper the expression ferroelectrets will be used. The early ferroelectrets were polarized cellular polymers, foremost polypropylene (PP), exhibiting high piezoelectric activity that exceeds PVDF.[22–26] Drawbacks of polarized cellular PP are its missing thermal charge stability and the absence of a significant $d_{31}$ activity. Due to these limitations, alternative ferroelectret materials, mostly fluorocarbons, have been investigated.[27–41] As a rule, these systems are characterized by a significant and thermally more stable $d_{33}$ piezoelectric response. This makes it possible to implement on their basis rather efficient vibration-based micro-energy harvesters.[42–49] A promising new development are parallel tunnel films.[50–52] These consist, for example, of two fluorinated polyethylene propylene (FEP) films partly fused together at elevated temperatures with enclosed air-filled tunnels and surface metallization (Figure 1A). Beside their superior electret properties as well as their far better thermal stability than PP, these structures exhibit not only similar longitudinal piezoelectric coefficients as piezoceramics but also have a large $d_{31}$-activity. This allows their use in energy harvesters based on the transverse piezoelectric effect, including cantilever systems.[50,51,53]

A recently presented example is an energy harvester where the seismic mass is placed on the center section of a ferroelectret strip, which in turn is fixed at both ends.[50,51] Consequently, when the support structure is subjected to an acceleration $a$, the ferroelectret film undergoes a dynamic stretching due to the inertia of the seismic mass. However, such harvesters, while generating large normalized power outputs, lack the robustness of ceramic implementations.

A more robust system based on an air-spaced cantilever structure was recently reported.[55] This energy harvester

![Figure 1](image-url)
consists of a parallel-tunnel ferroelectret, stretched by a cantilever beam which is subjected to an acceleration $a$. The ferroelectret film was mounted at a fixed distance $h$ from the neutral axis of the cantilever beam. A theory was offered which explained the dependency of the output power and resonance frequency on the seismic mass. It was also shown that the resonance frequency mainly depends on the stiffness of the cantilever beam. However, for accelerations above $0.06 \, g$, the generated power increases more slowly than expected theoretically, due to an asymmetrical stretching of the film.

In the present paper, significant improvements of the harvester output power are achieved by varying the distance $h$ (Figure 1) and utilizing different values of mechanical pre-stress. The theory of the previous work is shown in detail and used to explain the influence of different distances $h$. The influence of the pre-stress on the output power and the resonance frequency is also addressed.

2 | THEORY

When the cantilever base is subjected to an acceleration $a$ in $z$-direction, the tip mass is deflected by inertia into the negative $z$-direction from its position of equilibrium and forms an angle $\varphi$ with the cantilever’s plane [(see Figure 1D)]. The deflection $z$ of the free end of a cantilever depends on the seismic mass and thus is the result of a point force $F$ concentrated at its free end pointing into the negative $z$-direction. The thereby obtained deflection $z$ is given by

$$z = \frac{FL^3}{3YI},$$

(1)

where $L_C$ is the length of the cantilever, $Y$ its Young’s modulus and $I$ the moment of inertia of the beam. It should be mentioned that the force $F$ is also pointing in the same direction as the inertia induced deflection $z$. For small $z$ deflections, the displacement of the tip of the cantilever in the $x$-direction can be neglected. The transverse contraction of the beam and the ferroelectret film is also neglected. The angle $\varphi$ can be expressed as

$$\varphi = \frac{3}{2} \frac{z}{L_C}.$$  

(2)

The change of the length of the ferroelectret film is then geometrically determined by the intercept theorem, still neglecting the displacement of the cantilever tip in $x$-direction, as suggested by Beléndez et al.\cite{55} Under these assumptions one obtains:

$$\Delta L = h\varphi = \frac{3hz}{2L_C}.$$ 

(3)

Since the $z$ axis is defined as the direction of acceleration and the $x$ axis is the perpendicular axis, the equation of motion for the cantilever’s tip in $z$-direction can be written as:

$$\ddot{z} + 2\zeta\omega_0 \dot{z} + \omega_0^2 z = -a$$ 

(4)

and for a sinusoidal steady-state motion this yields to

$$z = \frac{-a}{\omega_0^2 - \omega^2 + 2j\zeta\omega_0\omega},$$ 

(5)

where $\omega$ is the exciting angular frequency of the cantilever base, $\omega_0 = \sqrt{k_C/m}$ the resonance frequency of the undamped harmonic oscillator of the beam which depends on the cantilever stiffness $k_C$ and the damping constant $\zeta$ of the beam. In this approach the influence of the spring constant $k_f$ and the damping constant of the ferroelectret on the resulting cantilever properties are neglected. Substituting $z$ in Equation (3) the film’s elongation $\Delta L$ can then be expressed as follows:

$$\Delta L = \frac{3h}{2L_C} \cdot \frac{-a}{\omega_0^2 - \omega^2 + 2j\zeta\omega_0\omega}.$$ 

(6)

Using the direct piezoelectric voltage coefficient $g_{31} = (U_{OC} F_1) / W_F$ linking the generated open circuit voltage $U_{OC}$ to the applied force $F_1$ on the ferroelectret film in $x$-direction (which differs from the force $F$ in $z$-direction) and utilizing the mechanical force constant $k_f$ of the ferroelectret film, the voltage $U_{OC}$ generated in open circuit can be written as:

$$U_{OC} = \frac{g_{31}}{W_F} F_1 = \frac{g_{31} k_f}{W_F} \Delta L = \frac{g_{31} k_f}{W_F} \frac{3h}{2L_C} \cdot \frac{-a}{\omega_0^2 - \omega^2 + 2j\zeta\omega_0\omega},$$ 

(7)

where $W_F$ is the ferroelectret film width. The rms-value of the voltage $U_R$ across a load resistance $R_L$ connected between the electrodes of the ferroelectret film can be written by means of a voltage divider as:

$$U_{R, rms} = U_{OC, rms} \frac{R_L C \omega}{\sqrt{1 + (R_L C \omega)^2}} = \frac{g_{31} k_f}{W_F} \frac{3h}{2L_C} \cdot \frac{R_L C \omega}{\sqrt{1 + (R_L C \omega)^2}}$$ 

(8)

$$\times \sqrt{\left(1 - \left(\frac{\omega}{\omega_0}\right)^2\right) + 4\zeta^2\left(\frac{\omega}{\omega_0}\right)^2},$$

where $C$ is the static capacitance of the ferroelectret film. Since this equation is only valid for small displacements,
the change of film capacitance is much smaller than its static value. Thus, the capacitance can be assumed to be constant. Increasing the acceleration \(a\) of the cantilever base results in further stretching of the ferroelectret film, and, thus, results in a higher output power, that is,

\[
P_R = \frac{U_{R,\text{rms}}^2}{R_L} = \left(\frac{g_{31}}{2L_CW_F} \frac{3hk_f}{\omega_0^2} \right)^2 \times \frac{a^2R_LC^2\omega^2}{\omega_0^2} \left[1 - \left(\frac{\omega}{\omega_0}\right)^2\right]^2 + 4\zeta^2\left(\frac{\omega}{\omega_0}\right)^2 \left[1 + R_LC\omega\right]^2
\]

(9)

It follows from Equation (9), that if the generated power is \(P_{h_0}\) for the smallest experimentally achievable distance \(h_0\) (in our case \(h_0 = 1\ mm\)), the power \(P_h\) corresponding to a distance of \(h\) is increasing quadratically according to

\[P_h = \left(\frac{h}{h_0}\right)^2 P_{h_0},\]

(10)

The experimental output power \(P_{\text{out}}\) generated by the air-spaced energy harvester for different distances \(h\) was obtained experimentally (see Experimental Section) from the relation

\[P_{\text{out}} = R_Li^2 = R_L\omega^2Q_{\text{rms}}^2,\]

(11)

where \(i\) is the current through the load resistor and \(\omega\) the angular frequency of the acceleration \(a\). The normalized value \(P_n\) is then given by

\[P_n = P_{\text{out}}\left(\frac{g}{a}\right)^2,\]

(12)

where \(g = 9.81\ m/s^2\) is the acceleration of gravity.

### RESULTS AND DISCUSSION

#### 3.1 Influence of film distance \(h\) on the output power

All measurements were performed at the same acceleration \(a = 0.1 \times g\), the same pre-stress and seismic mass \(m_s = 3.5g\), for a proper test of the power generated for different values of \(h\). The measurements indicate that the normalized output power increases from 16 to 438 \(\mu\)W for \(h = 1\ mm\) to \(h = 10\ mm\) (Figure 2A). The power decreases for larger distances \(h\). In all cases the resonance frequency shifts toward higher frequencies, indicating an increasing influence of the film stiffness \(k_f\) on the cantilever stiffness \(k_C\).

Note that in the present analysis \(k_C\) and \(k_f\) are assumed to be independent of each other, which is only valid for small angles \(\varphi\) and small values of \(h\) resulting in small film displacements \(\Delta L\). For larger angles \(\varphi\) and larger \(h\) values, \(k_f\) starts to influence \(\omega_0\) toward higher frequencies. According to the above presented theory, the film length variation \(\Delta L\) is assumed to be proportional to \(h\).

Increasing \(h\) enhances the stiffness of the film-cantilever system. In fact, when the air-tunnels are subjected to more stress in \(x\)-direction, the stiffness of the solid FEP layers enclosing the air tunnels becomes more and more dominant compared to the air-filled regions. This means that the ferroelectret stiffness \(k_f\) is no longer negligible compared to the beam stiffness \(k_C\). This leads to an effectively larger \(k_C\) in the above theory which then results in a shift to higher resonance frequencies (Figure 2A) and at larger distances \(h\) to even smaller normalized power see (Figure 2A).

The first reason for the decrease of the power is related to the fact that the voltage generating tunnels of the ferroelectret become more and more rigid with increasing \(h\), leading to a smaller voltage output (smaller \(g_{31}\) and...
thus to a decrease of the power generation. This effect, for the present devices, is noticeable starting from a film distance of \( h = 5 \text{mm} \) (Figure 2B). The second reason for the flattening of the generated output signal at larger \( h \)-values is mainly due to the asymmetry of the ferroelectret stretching, when the beam is bent in positive and negative \( z \)-direction, as was demonstrated in previous work.\(^{[53]}\) The reason for such asymmetry is the different mechanical stress the ferroelectret film is exposed to, when the beam moves down (stretching) and up (loosening).

### 3.2 Influence of pre-stress on output power and device stability

In order to avoid such asymmetry and to achieve a symmetric deformation compared to the initial state of the ferroelectret film during operation, a relocation of the operating point of the device by pre-stressing the ferroelectret film is investigated. Two distances \( h \) between the neutral axis of the cantilever beam and the ferroelectret film were considered, namely, 1 and 5 mm, respectively, the latter being close to the film distance with maximum normalized power output (Figure 2B). The pre-stressing of the film has to be carried out using the setup in Figure 1. The clamp at the end of the cantilever beam (see Figure 1C) is fixed and represents the seismic mass \( m_s \).

On the side of the cantilever base, a movable clamp is used that can slide in a reproducible way in a guide structure. This structure is controllable in the negative \( x \)-direction by a micrometer screw. By such sliding the produced strain results in a pre-stress of the ferroelectret film. The term pre-stress is used since the performed straining leads to a slight bending of the beam, which even after mechanical relaxation results in a remaining pre-stress on the ferroelectret. If under such conditions the cantilever is set into vibrations, the individual tunnels will be stretched when the cantilever is bent downward and the stress is partially released when bent upward. The difference to a stress-free bending of a displaced ferroelectret is that under upward bending the film still stays under stress which is not the case without pre-stress. Advantageous for the pre-stress is that the same deformation occurs in both bending directions leading to an equal energy gain in both directions of acceleration. The disadvantage, however, is that an excessive pre-stress of the sample leads to a decrease in the \( g_{31} \)-coefficient, and, therefore, to a decrease in the generated power (see Equation 9). The optimum pre-stress is difficult to predict and has to be determined experimentally. In order to find the optimum pre-stress for our energy harvester, measurements under different pre-stress conditions were conducted using the same seismic mass of \( m_s = 3.5 \text{g} \) and a fixed acceleration \( a = 0.1 \times g \).

For \( h = 5 \text{mm} \) a 2\% strained sample leads to a twice as large peak power of 737 \( \mu \text{W} \) compared to the unstrained structure. For \( h = 1 \text{mm} \) the output power is relatively even more enhanced up to 253 \( \mu \text{W} \) by straining to 3.66\%, however, still below the value reached for \( h = 5 \text{mm} \) (Figure 3A and B). Unfortunately, one can uniquely specify the pre-strain applied to the samples. The physically important property is, however, the pre-stress which cannot be determined quantitatively. Even so, the parameter stress or pre-stress will be mostly used in the following discussions.

Considering the nonlinear behavior of the stress-strain curve of the used ferroelectret as described before\(^{[50]}\), a reallocation of the working point also influences the stiffness of the ferroelectret film and consequently the \( g_{31} \)-coefficient. Since the dynamic displacement \( \Delta L \) increases with the distance \( h \), the stiffness enhancement of the film-cantilever system for larger \( h \) is more noticeable (Figure 3C and D).

Despite the fact that the dynamic deformation of the film while vibrating is much larger for larger \( h \) (see Equation 3), it can be noted that the maximum power output of the pre-stressed film for \( h = 1 \text{mm} \) corresponds approximately to the output power of the cantilever structure without pre-stress using a distance of \( h = 5 \text{mm} \) (Figure 3C and D). The comparability of the two maximum power outputs indicates that the limit is determined neither by the distance \( h \) of the ferroelectret film nor by the pre-stress but rather by a common source which has to be looked for in the ferroelectret film itself. Since for both cases (increasing of distance or strain) the power output drops below its maximal value, the reason for the decrease must be assumed to be in the film itself. It is most likely originating from the deformation of the tunnels after reaching saturation, where any further deformation starts to strongly decrease the piezoelectric \( g_{31} \)-voltage coefficient. Under positive or negative loads the thickness of the tunnels decreases to a value, where the induced strain mainly acts on the already strongly elongated FEP framework, instead of compressing the tunnels any further. The consequence thereof is a strongly reducing additional strain, leading to a reduction of the power generation.

A further interesting benefit of utilizing a pre-stress is the improved temporal stability of the output power as can be seen from Figure 4A. For this experiment, the power output of the energy harvester was determined for an acceleration of \( a = 0.1 \times g \) and a seismic mass of \( m_s = 3.5 \text{g} \). Approximately 9 million cycles were applied, which correspond to approximately 70 hours of operation at a frequency of 35Hz, which is a reasonable stress test. Pre-stressing of the film results in a stable output power of 720 \( \mu \text{W} \) over the measurement duration, whereas the absence of pre-stress leads to a steady increase of the output power.
**FIGURE 3**  A, B, Frequency responses of the normalized power of energy harvesters with various pre-stresses of the ferroelectret film introduced by pre-straining the ferroelectret films to the indicated values by using distances $h = 5\, \text{mm}$ and $1\, \text{mm}$, respectively. C, D, Normalized power at the resonance frequency and the resonance frequency for each pre-stress by using a distance $h = 5\, \text{mm}$ and $1\, \text{mm}$ from the neutral axis of the beam, respectively. The ordinates of (C) and (D) are scaled in the same way to allow a direct comparison of the two measurements. All measurements were performed at the same acceleration $a = 0.1 \times g$ and using the same seismic mass $m_s = 3.5\, g$.

**FIGURE 4**  A, Long-term stability of the normalized output power at resonance frequency for two different initial strains. The cantilever used in this experiment features a distance of $h = 5\, \text{mm}$. The measurements are conducted using the same acceleration $a = 0.1 \times g$ and seismic mass of $m_s = 3.5\, g$. B, Normalized output power at resonance frequency for increasing acceleration.

Another advantage of the pre-stressed ferroelectrets compared to the stress-free ones is the enhancement of the power stability as a function of acceleration as shown in Figure 4B. When no pre-stress is used, the measurements indicate a decay of the normalized power as soon as an acceleration of $a = 0.04 \times g$ is reached. This limit can
be enhanced up to $a = 0.1 \times g$, when a pre-strain of 2% is applied to the ferroelectret film. In addition, the output power is enhanced from 270 to 737 $\mu W$.

### 3.3 Viscoelastic property

Considering the viscoelastic and plastic properties of solid FEP-films used to manufacture parallel-tunnel ferroelectrets, one can expect that under pre-stress the ferroelectret film behaves accordingly. In order to examine such effects a fixed pre-strain was applied to the ferroelectret and its impact on three aspects was investigated. The first aspect is the constancy of the pre-stress for a given pre-strain. It was measured using a universal testing machine (Inspekt table 5 kN, Hegewald & Peschke). Hereby, the pre-strain is increased in steps of 0.33% up to 4% while simultaneously measuring the force (as indication for a varying stress) that results from keeping the applied strain constant (Figure 5A). For each pre-strain the position is maintained for 60 minutes while measuring the force developing while preserving the reached position (Figure 5A). To avoid overshooting, a small velocity of $0.1 mm s^{-1}$ was used to move from one strain to another.

The measurement shows different creep behavior of the ferroelectret film depending on the pre-strain. By using 0.33% pre-strain to stretch the ferroelectret film, a negligible decay of the resultant initial stress is reached after 60 minutes. On the other hand, when using a pre-strain of 2%, which corresponds to the optimal strain regarding the output power, a decay of approximately 4% of the initial pre-stress is measured after 60 minutes. A drop of 10% of the initial pre-stress has been recorded for an even higher pre-strain of 3.7%.

The second aspect was to find out whether the mechanical relaxation has an effect on the generated power at the resonance frequency of 35Hz. Therefore the constancy of the power was examined, when the harvester is not used continuously. Two measurements were conducted for each pre-strain. The first measurement is directly carried out after the adjustment of the pre-strain and the second measurement is conducted 24 hours later. The pre-strain is increased by the aforementioned steps in order to compare the mechanical and electrical properties under almost the
FIGURE 6  Schematics of experimental setup used for energy harvesting evaluation

same conditions. The resulting output powers show almost the same values (see Figure 5B) with a small increase in power for 2% pre-strain.

The third aspect is the hysteresis of the output power for ascending and descending pre-stress (Figure 5C). The pre-stress is increased by increasing the strain in steps of 0.33% until a strain of 3.66% is reached and decreased by reducing the pre-strain with the same step size down to 0%. For each pre-strain, the frequency response of the harvester is measured and the achieved amplitude at the resonance frequency is noted. Therefore, each pre-strain is maintained during the measurement time of approximately 30 minutes. For an ascending pre-strain, the highest reached amplitude is 737 μW at 2% pre-strain, whereas a descending pre-strain shows a different amplitude and different optimal pre-strain, namely 1029 μW and 1.66% respectively. Starting from a pre-strain of 2.66% the hysteresis becomes thinner (if the pre-strain increases) and the achieved amplitudes for both ascending and descending pre-stress become more similar.

The increase of the output power for ascending pre-strain can be explained by the fact that the stiffness of the film has decreased due to the excessive stretching. The decrease of the stiffness $k_f$ can be explained by the viscoelasticity of the FEP films used to manufacture the ferroelectret. This means a larger deformation of the air-filled tunnels can be reached for the same force, resulting in a larger piezoelectric voltage constant $g_{31}$. This hysteresis can also be used to improve the performance of the energy harvester without adjustment of the geometry. Before the energy Harvester starts to operate, the ferroelectret film can be stretched and then relaxed until the new optimal working point is reached. When the energy harvester is set into vibration, a maximum power of 1029 μW can be reached. Note that all hysteresis measurements are reproducible for pre-strains not exceeding 4%. An excessive pre-strain results in a plastic deformation of the samples and therefore in a completely different behavior. A detailed study about the influence of viscoelasticity on the output power is beyond the scope of this work and will be published separately.

4  |  EXPERIMENTAL SECTION

The smallest experimental distance $h_0$ was achieved by placing the ferroelectret film at a distance of 1 mm above the neutral axis of the cantilever beam. Afterwards, the distance $h$ is varied up to 20 mm. The seismic mass is designed as a hollow structure to minimize its weight. Furthermore,
all parts including screws are made of plastic. Since the characteristics of different ferroelectret films are likely to differ slightly, only a single film was used for all measurements presented in this paper. Thereby, the change in the generated power during the experiments is exclusively caused by only one experimental parameter, namely the different distance $h$. Therefore, all measurements have been conducted using the same acceleration and seismic mass. This suppresses the influence of unknown factors, such as film slipping from the clamp that may be triggered by large accelerations particularly for larger $h$. For changing the distance $h$, the cantilever structure is modified accordingly. In order to avoid different mechanical pre-stress of the film, each time the harvester is assembled for a new distance $h$, the ferroelectret film length is fixed between the two 3D printed clamps by a spacer block with a fixed length allowing for an undisturbed dismantlement and installation.

The ferroelectret film used in this study is made of fluorinated polyethylene propylene (FEP) and has the dimensions of $10 \times 40 \text{mm}^2$. It exhibits static and dynamic piezoelectric $g_{31}$-coefficients of $1.9 \text{V/mN}^{-1}$ and $0.8 \text{V/mN}^{-1}$, respectively. The energy-harvesting device is an air-spaced cantilever arrangement that was mostly made by additive manufacturing technique known as fused deposition modeling (FDM). The used cantilever material hereby was polylactide acid (PLA) with 15% infill and a gyroid fill pattern. The cantilever beam of dimension $10 \times 30 \text{mm}^2$ is responsible for the stiffness of the mechanical resonant system. The ferroelectret film is incorporated into the structure by clamping it between the cantilever base and the seismic mass (Figure 1B and C). The metal electrodes are connected to an external electrical network consisting of the load resistor $R_L$ in addition to a charge amplifier and a voltage meter (see Figure 6). The device was tested by exposing it to vibrations with an acceleration $a$ generated by a shaker (Brüel&Kjaer type 4809). The generated power was determined as a function of frequency by terminating the ferroelectret with a load resistor $R_L = \frac{1}{\omega_0^2 C}$, where $\omega_0$ is the mechanical resonance frequency of the device and $C$ the static capacitance of the ferroelectret.

5 | CONCLUSION

In conclusion, the dependence of the power output of an energy harvester arrangement on the distance between the ferroelectret and the cantilever beam has been investigated. This harvester can be easily manufactured using additive manufacturing technique (3D printing) and provides a modular assembly which ensures reproducibility. Such a harvester generates a normalized output power of more than 1 mW at a resonance frequency of about 35 Hz for a seismic mass of 3.5 g and an acceleration of $0.1 \times g$. It was experimentally verified that the power generated at the resonance frequency can be stabilized over the measurement duration of 70 hours as well as for different accelerations up to $0.1 \times g$ by using mechanical pre-stress. The influence of varying the distance between the neutral axis of the cantilever beam and the ferroelectret film shows an excellent agreement with theory up to a distance of $h = 10 \text{mm}$. Thus, the presented energy harvester proves to be particularly suitable for low acceleration amplitudes up to $0.1 \times g$. It turns out to be a reproducible, environmentally friendly by using polylactide acid for the cantilever structure and particularly robust system with relatively high sensitivity.

The energy output of a cantilever based energy harvester can be improved by using two ferroelectret films to build a bimorph cantilever structure. The ferroelectret films should be placed at the optimal distance from the neutral axis, which can be investigated experimentally. Such a structure offers twice as much output power than when using a single film. When each film is optimally pre-stressed, the output power can be further enhanced to reach the range of several milliwatts.

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CONFLICT OF INTEREST

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

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