

Auxetic piezoelectric energy harvesters for increased electric power output

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Abstract: This letter presents a piezoelectric bimorph with auxetic (negative Poisson's ratio) behaviors for increased power output in vibration energy harvesting. The piezoelectric bimorph comprises a 2D auxetic substrate sandwiched between two piezoelectric layers. The auxetic substrate is capable of introducing auxetic behaviors and thus increasing the transverse stress in the piezoelectric layers when the bimorph is subjected to a longitudinal stretching load. As a result, both 31- and 32-modes are simultaneously exploited to generate electric power, leading to an increased power output. The increasing power output principle was theoretically analyzed and verified by finite element (FE) modelling. The FE modelling results showed that the auxetic substrate can increase the transverse stress of a bimorph by 16.7 times. The average power generated by the auxetic bimorph is 2.76 times of that generated by a conventional bimorph.

Energy harvesting from ambient mechanical vibrations has been a worldwide effort in the past two decades due to its potential to provide sustainable supply for portable electronic devices and wireless sensors. Hereinto, piezoelectric energy harvesting has attracted more attention than other vibration energy harvesting methods such as using electromagnetic¹ and electrostatic² effects due to its advantages including simple structure, scalability and high power output^{3,4}. The reported electric power outputs of piezoelectric energy harvesters (PEHs) range from nanowatts to milliwatts⁵⁻⁸, which highly depend on the piezoelectric coupling coefficient of the piezoelectric material. There are dramatic performance improvements in new piezoelectric materials, such as piezoelectric single crystals PZN-PT and PMN-PT, but the wide use of these materials for energy harvesting in the near future is still in question due to their high cost⁹. This letter will introduce an unconventional material behaviors, auxetic behaviors, to PEHs to increase the power output. Combing piezoelectric transducers and composites with auxetic materials have been investigated before for sensing^{10,11} and actuating¹² applications but the use of auxetic bimorphs for energy harvesting has not been reported yet.

It is well known that all the PEHs use one of the operating modes (31-, 33- or 15- mode) to generate electric energy. For instance, when a PEH is designed to work in the 31-mode, i.e. the stress along the 1-axis produces electric field along the 3-axis through the piezoelectric constant d_{31} , the generated stress in the 2-axis is usually negligible as it is very small and does not contribute to the power generation, although the piezoelectric constant d_{32} has the same magnitude as d_{31} . In this work, we use both 31- and 32-modes to generate electric power by introducing auxetic behaviors to piezoelectric bimorphs through a 2D auxetic substrate. An auxetic structure is characterized by a negative Poisson's ratio, that is, when the auxetic structure is stretched longitudinally, it expands transversely instead of contracting like a conventional structure with a positive Poisson's ratio and vice versa. While the piezoelectric bimorph with the 2D auxetic substrate is actuated in the 31-mode, the 32-mode is parasitically excited, i.e. the stress along the 2-axis is also induced and contributes to the power generation, leading to an increased power output. This hypothesis is verified by FE modelling in the letter. The average power generated by the piezoelectric bimorph with an auxetic substrate is 2.76 times of that with a conventional substrate.

Fig.1 (a) shows a conventional piezoelectric bimorph operating in the 31-mode for energy harvesting. The piezoelectric bimorph comprises a central metallic substrate and two piezoelectric layers on the top and the bottom. The piezoelectric layers are poled along the 3-axis and electrodes cover the surfaces perpendicular to the 3-axis. When a uniaxial stretching load is applied, the open-circuit voltage generated across the electrodes is

$$U_{oc} = 2 \cdot \left(\frac{d_{31}\overline{\sigma_{11}}}{\epsilon_{33}} + \frac{d_{32}\overline{\sigma_{22}}}{\epsilon_{33}} \right) \cdot t_p \quad (1)$$

where $\overline{\sigma_{11}}$ and $\overline{\sigma_{22}}$ are the average longitudinal (along the 1-axis) and transverse (along the 2-axis) stress in the piezoelectric material, respectively; ϵ_{33} and t_p are the permittivity and layer thickness of the piezoelectric

material, respectively. When the load resistor matches the internal impedance of the bimorph (Eq. (2)), the bimorph outputs the maximum electric power, which can be approximated by Eq. (3) provided $d_{31}=d_{32}$.

$$R_L = \frac{1}{2\pi f C_p} = \frac{t_p}{\pi f \epsilon_{33} A} \quad (2)$$

$$P_{max} = \frac{U_{OC}^2}{4R_L} = \frac{\pi f t_p A d_{31}^2}{\epsilon_{33}} \cdot (\overline{\sigma_{11}} + \overline{\sigma_{22}})^2 \quad (3)$$

where C_p is the capacitance between the electrodes; A is the electrode area. Eq. (3) clearly suggests that $\overline{\sigma_{22}}$ has the same power generation ability as $\overline{\sigma_{11}}$ if it is properly designed, and the power output is proportional to $(\overline{\sigma_{11}} + \overline{\sigma_{22}})^2$.

For conventional bimorphs, because the Poisson's ratios of the piezoelectric materials and the substrate are both positive and about the same in magnitude, they contract transversely at about the same rate. In such a case, there is no external force applied on the piezoelectric layer in the transverse direction. Therefore, $\overline{\sigma_{22}}$ is close to zero and hardly affects the power generation. In other words, only the 31-mode is responsible for the power output for the conventional bimorph. However, if the substrate has a negative Poisson's ratio and thus expands transversely, it will generate a transverse force on the piezoelectric layer since the piezoelectric layer has a different and positive Poisson's ratio. This force, if large enough, will force the piezoelectric layers to expand transversely, i.e. the piezoelectric layers also demonstrate auxetic behaviors. As a result, $\overline{\sigma_{22}}$ will be increased and has the same sign as $\overline{\sigma_{11}}$, therefore contributing to the power generation. In this case, both the 31- and 32-modes are engaged in the power generation simultaneously, leading to an increased power output.

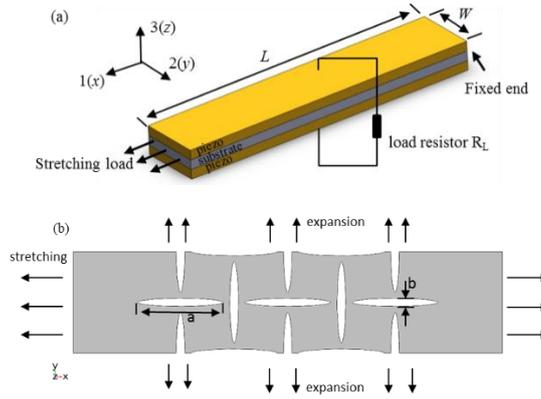


Fig. 1 (a) A typical piezoelectric bimorph for energy harvesting (b) a 2D auxetic substrate to replace the conventional substrate in the bimorph

To verify this hypothesis, FE modelling was performed in COMSOL to compare the power output of piezoelectric bimorphs with a conventional bulk substrate (BS-bimorph) and a 2D auxetic substrate (AS-bimorph). The FE modelling used the same configuration as Fig. 1 (a). Structural steel was used as the substrate material. For the AS-bimorph, the auxetic substrate shown in Fig. 1 (b) was used, which is a 2D metallic sheet with a square array of mutually orthogonal elliptical voids and was previously studied by Taylor *et al.*¹³. The auxetic behavior of the substrate can be controlled by the aspect ratio a/b . When the aspect ratio is small, the substrate has a positive Poisson's ratio. As the aspect ratio increases, the Poisson's ratio decreases monotonically cross zero to negative values. This letter will use an aspect ratio of 10, which provides large auxetic behaviors. The elliptical voids of the substrate were filled with epoxy. Polyvinylidene fluoride (PVDF) was selected as the piezoelectric material due to its ability to sustain high strain. The PVDF layers were connected in series and then terminated with a load resistor. A stretching load was applied on the free tip of the bimorph along the x -axis in the form of a sinusoidal displacement (frequency: 10 Hz; amplitude: 0.1 mm). The key dimensions and material properties of the bimorphs are listed in Table 1. It is worth to note that the FE modelling of PEHs in COMSOL has previously experimentally validated¹⁴.

Table 1 The material properties and dimensions of the piezoelectric bimorphs used in the FE modelling⁴

Dimensions	values	PVDF properties	Values	Structural steel properties	Values
Length L (mm)	200	S_{11}^E (pPa ⁻¹)	365	Young's modulus (GPa)	200
Width W (mm)	50	S_{33}^E (pPa ⁻¹)	472	Poisson's ratio	0.33
t_p (mm)	0.05	d_{31} (10 ⁻¹² C/N)	21	Density (kg/m ³)	7850
Substrate thickness t_s (mm)	0.2	d_{33} (10 ⁻¹² C/N)	-33	Epoxy properties values	
Major axis a (mm)	20	d_{15} (10 ⁻¹² C/N)	27	Young's modulus (GPa)	0.7
Minor axis b (mm)	2	ϵ_{33}	12	Poisson's ratio	0.35
		Density (kg/m ³)	1700	Density (kg/m ³)	1250
		Poisson's ratio	0.34		

Fig. 2 presents the displacements of the AS- and BS- bimorphs along the x -axis (u_x) and the y -axis (u_y). It can be observed that the displacement fields of the AS-bimorph are severely distorted by the elliptical voids. While the AS-bimorph is stretched longitudinally, transverse expansions are observed. In other words, the AS-bimorph shows negative Poisson's ratio behaviors. For the BS-bimorph, as it is stretched in the x -axis, it is contracted in the y -axis, which is expected for a conventional substrate with a positive Poisson's ratio.

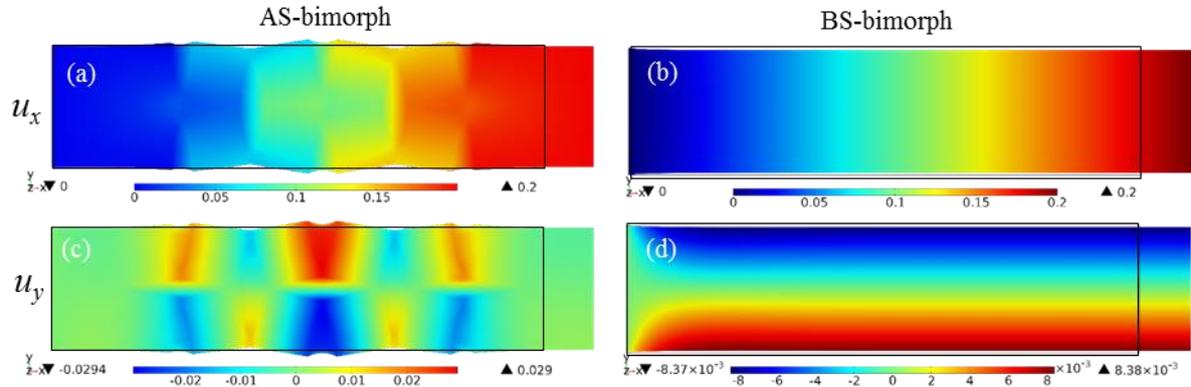


Fig. 2 Displacements of the bimorphs (unit: mm): (a) and (b) along the x -axis in AS- and BS-bimorphs, respectively; (c) and (d) along the y -axis in the AS- and BS-bimorphs, respectively. The deformation is scaled up by 100 times, and the black lines show the original shape of the bimorphs.

The electric power outputs of the AS- and BS- bimorphs are presented in Fig. 3. The BS-bimorph generates the maximum power of 0.25 mW when connected with a 400-k Ω load resistor. Connected with the same load resistor, the AS-bimorph generates 0.69 mW, which is 2.76 times of the power generated by the BS-bimorph. Apparently, the auxetic behaviors of substrate and the AS-bimorph have increased the power output. More precisely, the enhanced transverse stress level in the piezoelectric material caused by the auxetic behaviors has increased the power generation, which can be revealed by the stress distribution in the PVDF, shown in Fig. 4.

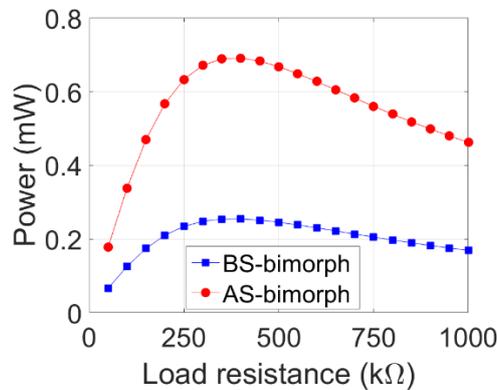


Fig. 3 Comparison of the electric power outputs between the AS- and BS- bimorphs

For the BS-bimorph, the longitudinal stress σ_{11} and the transverse σ_{22} are uniformly distributed in the x - and the y -axis directions except in the proximity of the fixed end. The average transverse stress $\overline{\sigma_{22}}$ is 0.06 MPa, which is negligible compared with the longitudinal average stress $\overline{\sigma_{11}}$ of 2.02 MPa and generates little power output. Therefore, for the BS-bimorph, the power output is mainly produced by 31-mode. For the AS-bimorph, $\overline{\sigma_{22}}$ is increased by 16.7 times to 1.0 MPa due to the auxetic behaviors, which is 40% of the $\overline{\sigma_{11}}$ (2.4 MPa) and contributes a significant amount of power generation. Therefore, For the AS-bimorph, both the 31- and 32-modes generate electric power outputs.

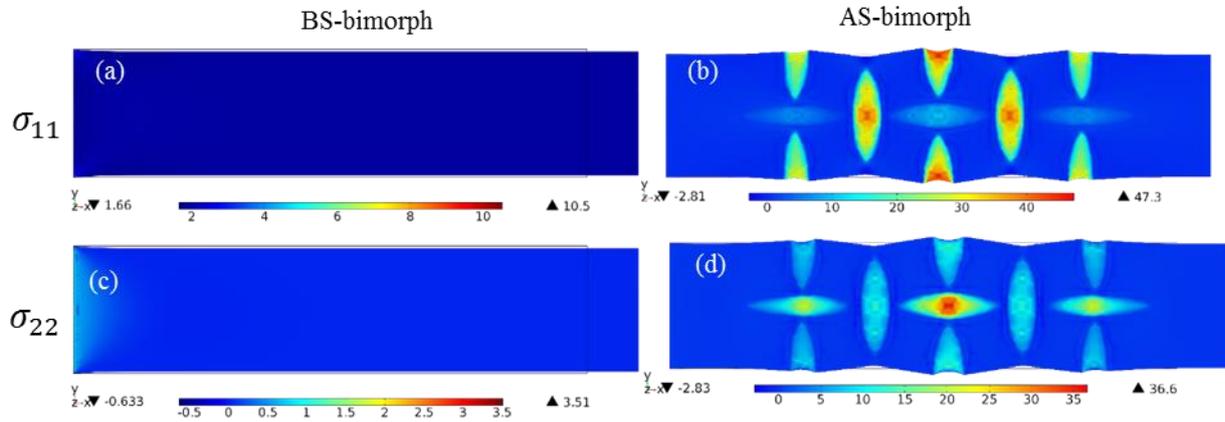


Fig. 4 Stress of the PVDF (unit: MPa): (a) and (b) along x -axis in BS- and AS-bimorph, respectively; (c) and (d) along y -axis in the BS- and AS-bimorph, respectively. The deformation is scaled up by 100 times.

In summary, this letter presented a preliminary study on a method to increase the power output of a piezoelectric bimorph by introducing an auxetic substrate. The auxetic substrate transferred the auxetic behaviors to the piezoelectric layers and thus increased the transverse stress. By using this method, both the 31- and 32 modes were engaged in the electric power generation, which is different from conventional bimorphs, where only the 31-mode contributes to the power output. The power output of the bimorph with the auxetic substrate was 2.76 times of a conventional bimorph.

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