High-efficiency Compressive-mode Piezoelectric Energy Harvester

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Energy Harvesting

- Energy harvesting is a nascent technology by which energy is extracted from ambient vibrations, converted to electricity, and stored for low-power electronic devices.
- Piezoelectric energy harvesters (PEHs) have the advantages of high voltage output, high power density and simple configurations.

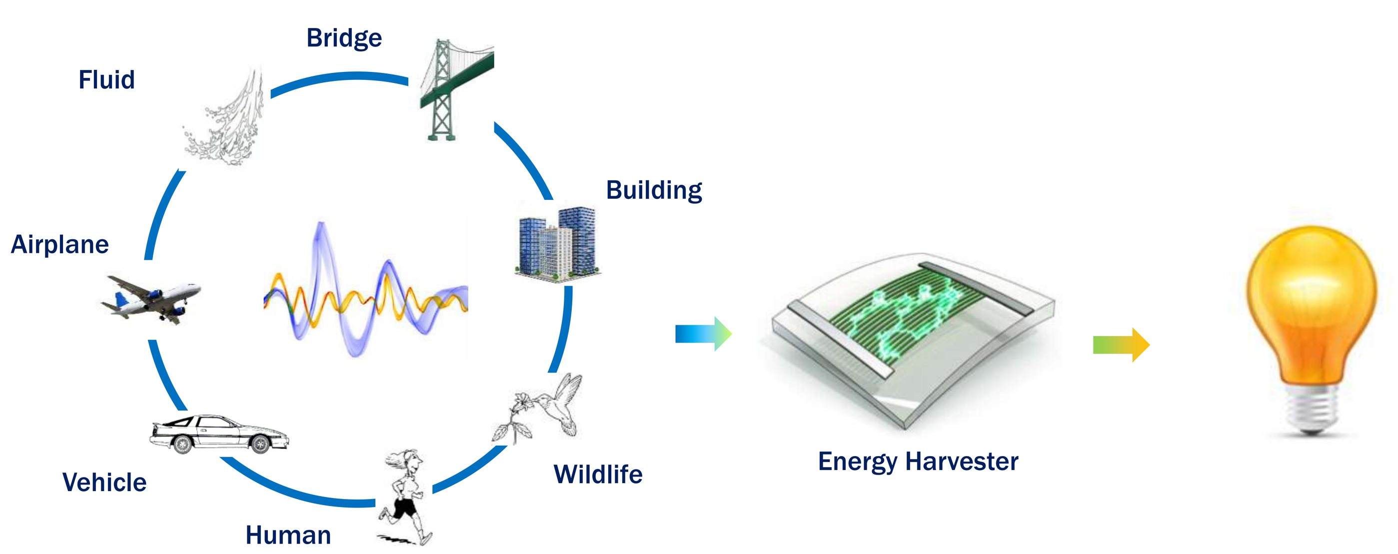

Fig. 1. Vibration-based energy harvesting process

Motivation

- Batteries of implantable devices such as pacemakers need to be replaced by surgery in 5-10 years, which is painful, expensive and easily causes infections.
- Wireless sensor networks such as the forest fire monitoring system consist of a vast number of sensors distributed over thousands of miles. Replacement of batteries for such a large number of sensors is time-consuming and costly.

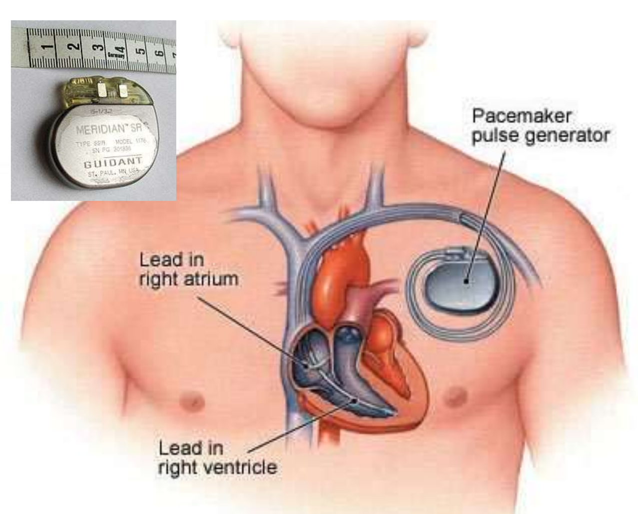

Fig. 2. Artificial pacemaker

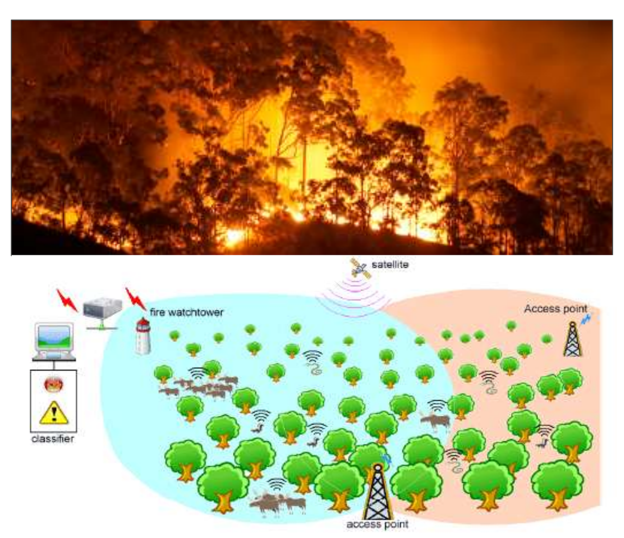

Fig. 3. Forest fire monitoring system

Challenges of the conventional PEH

- Low power output
- Narrow working bandwidth
- Unidirectional sensitivity

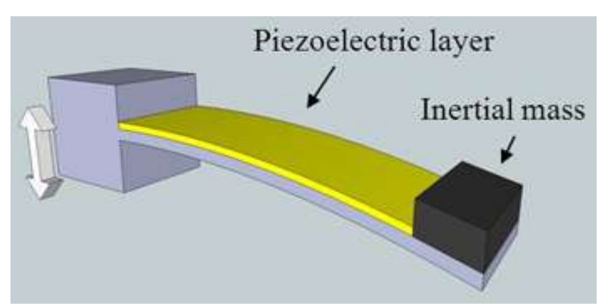

Fig. 4. Conventional PEH

HC-PEH

- The high-efficiency compressive-mode piezoelectric energy harvester (HC-PEH) consists of a pair of elastic beam, a flex-compressive center and two proof masses.
- Three mechanisms: 1) the multi-stage force amplification; 2) the compressive mode; 3) the geometric nonlinearity are introduced into the new HC-PEH.

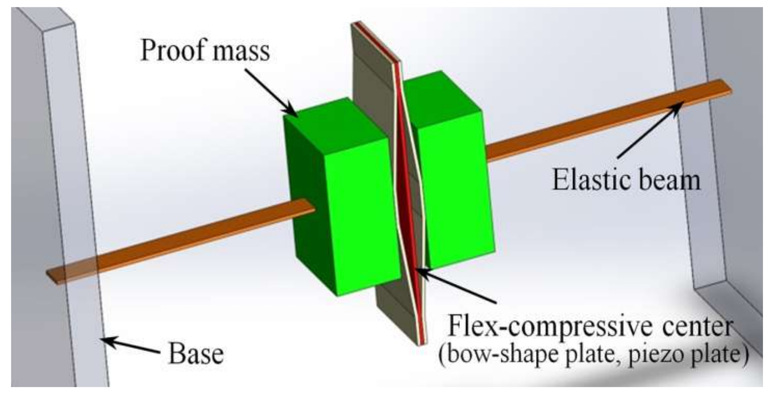

Fig. 5. Schematic diagram of the HC-PEH

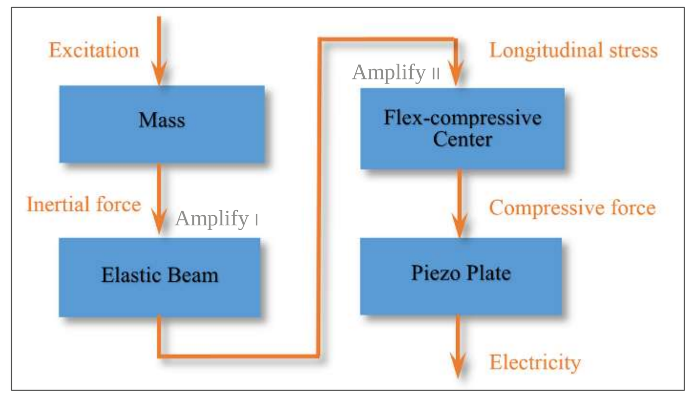

Fig. 6 Multi-stage force amplification mechanism

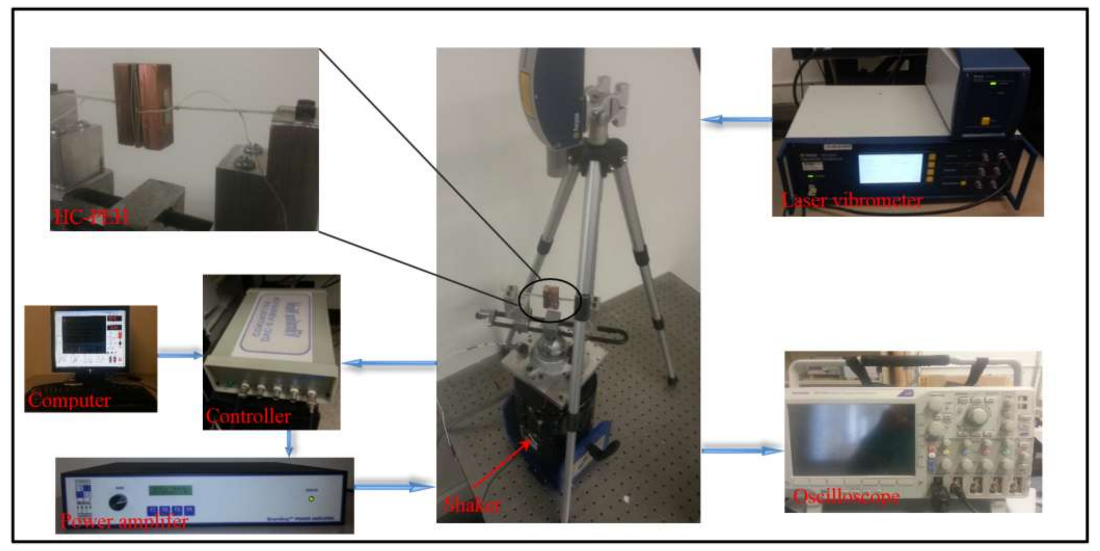

Fig. 7. Prototype & experimental setup

Theoretical Analysis

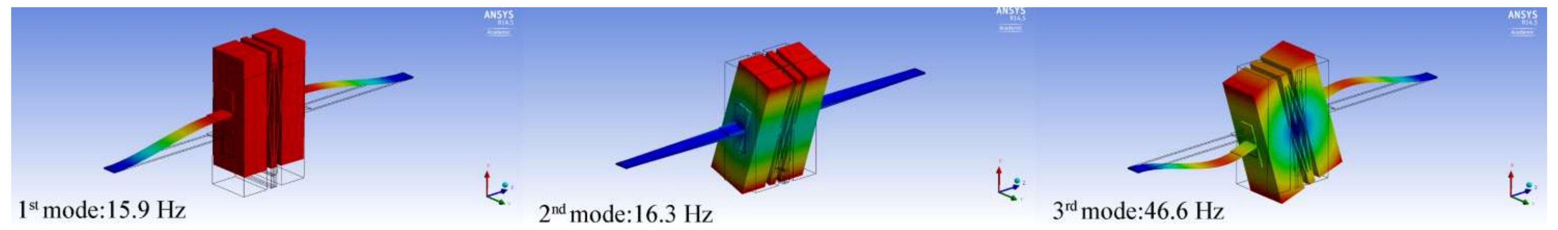

Fig. 8. Mode shapes of the first three modes from the *FEM* simulation

Governing Equations:

$$mx''(t)+c_1x'(t)+c_2\,|\,x'(t)\,|\,x'(t)+k_1x+k_3x^3+\theta v(t)=mz''(t)$$

$$C_p v'(t)+\frac{1}{R}v(t)=\theta x'(t)$$

The harmonic balance method and the multiple scale method are used to get the approximate analytical solution of the governing equations.

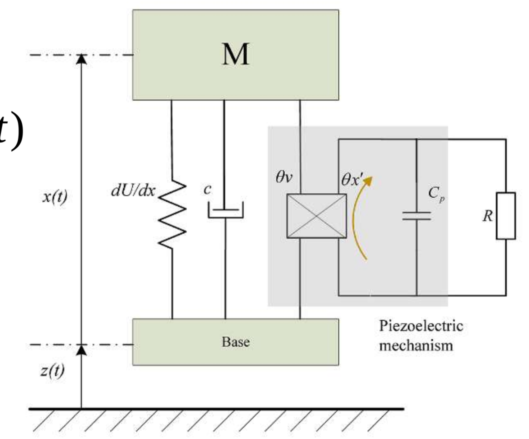

Fig. 9. Equivalent schematic of the HC-PEH with an external resistive load

Results

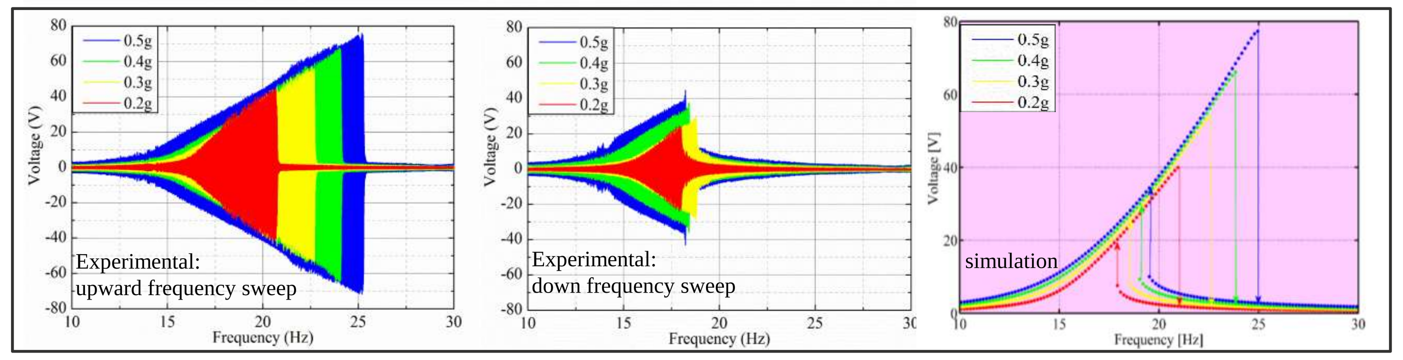

Fig. 10. Voltage responses of the HC-PEH with an optimal external resistor of 100 KΩ.

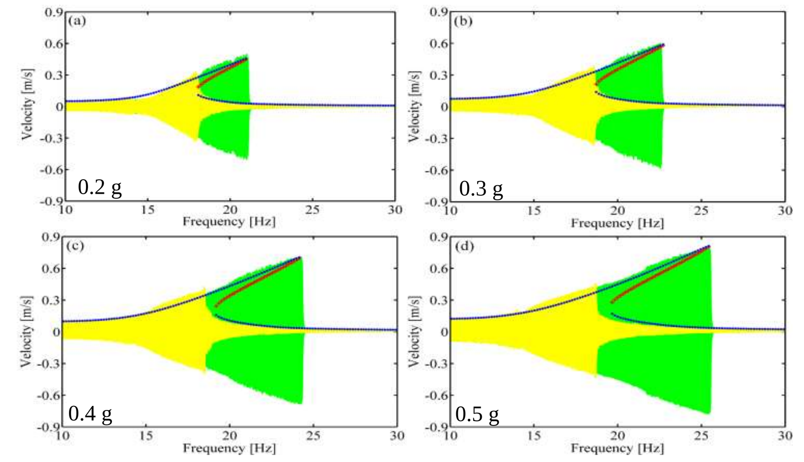

Fig. 11. Velocity responses of the HC-PEH under different excitations. The dotted lines denote simulation results and the colored regions represent experimental data.

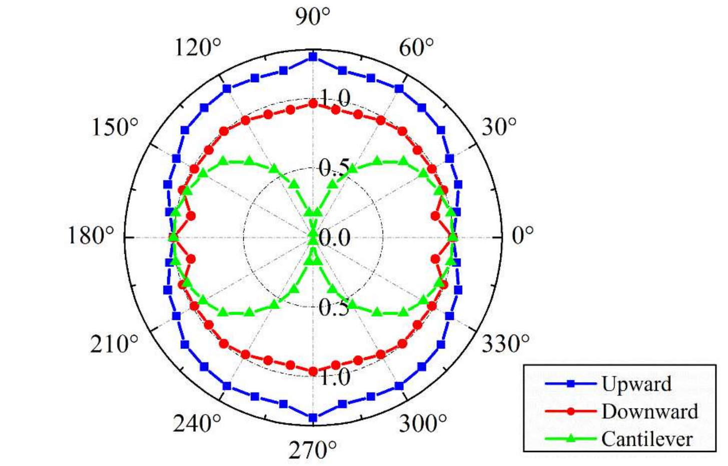

Fig. 12. Peak voltage responses normalized to the 0° voltage . The excitation direction is shifted constantly from parallel to perpendicular to the tested PEHs.

- The analytical results agree well with the experimental data in both mechanical and electrical responses.
- Strong nonlinear oscillations are observed with distinct jump phenomena.
- The bandwidth (> 1 mW) 12 Hz is achieved under an excitation of 0.5 g.
- The response of the HC-PEH is nearly unchanged under different excitation directions; in contrast, that of the conventional cantilever PEH is seriously attenuated (Fig. 12) .

Reference	Material	Dimensions (mm^3 · number)	Frequency (Hz)	Acceleration ($m\,s^{-2}$)	Power (mW)	Power density ($mW\,cm^{-3}$)	NPD ($kgsm^{-3}10^3$)
Zhao. 2012	PZT	13 × 2.5 × 1 · 2	73	14.5	0.0174	0.27	0.0013
Dhakar. 2013	PZT-5 A	31.9 × 6.4 × 0.5	36	1.96	0.04	0.38	0.0989
Kim. 2010	PZT-5 A	53 × 31.8 × 0.5	109.5	2.5	~0.53	0.62	0.1
Wu. 2013	MFC	36 × 16 × 0.3 · 3	18	1	~1.5	2.9	2.9
Liang. 2010	PZT-5 A	49 × 24 × 0.5	42	14.1	2.5	4.25	0.02
Gu. 2011	PZT-5 A	26 × 6.4 × 0.5 · 2	20.1	3.92	1.53	9.01	0.59
Li. 2011	Piezo stack	3141	87	9.8	14.6	4.65	0.05
Dai. 2009	PZT-5 H	12 × 10 × 1	51	9.8	2.11	17.58	0.183
Qiu. 2014	PZT	12 × 6 × 1	38	5.88	0.39	5.4	0.1567
Arrieta. 2013	Quickpack	46 × 20.6 × 0.25 · 2	~20	2.45	7.07	14.9	2.49
Xu. 2012	PMN-PT	25 × 5 × 1 · 2	102	31.4	3.7	29.6	0.03
This work	PZT-5 H	32 × 15 × 0.7	21	1.96	20.7	61.6	16
			25.7	4.9	54.7	162.8	6.8

Table 1. Performance comparison of the HC-PEH prototype with the state-of-the-art PEHs

Generally, the power output of a PEH is of 1 μW - 1 mW. The HC-PEH prototype has a maximum power output of 54.7 mW, which is about one order of magnitude higher than that of state-of-the-art PEHs under the similar conditions.

Conclusions

- The HC-PEH prototype shows a broad working bandwidth (12 Hz), an outstanding capability of high power output (54.7 mW), and a superb multi-directional sensitivity characteristic (no attenuation) .

Zhengbao Yang, Yang Zhu, and Jean Zu. "Theoretical and experimental investigation of a nonlinear compressive-mode energy harvester with high power output under weak excitations." Smart Materials and Structures 24.2 (2015): 025028.

Zhengbao Yang, and Jean Zu. "High-efficiency compressive-mode energy harvester enhanced by a multi-stage force amplification mechanism." Energy Conversion and Management 88 (2014): 829-833.