Advancing the performance of energy harvesting for structural health monitoring

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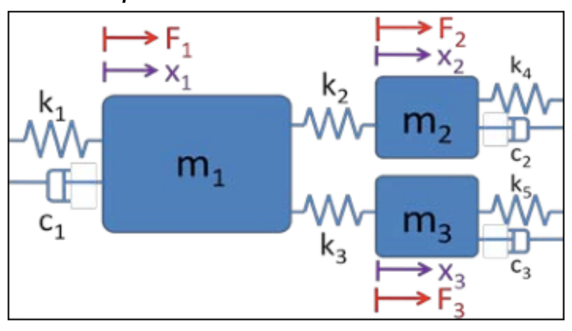
A multi-degree-of-freedom electrostatic energy harvester

Problem targeted: Narrow operational frequency band.

Proposed solution: With n number of proof mass, the system would have n number of resonant frequencies. Through designing the parameters: mass *m*, spring stiffness *k* and damping coefficient *c*, the resonant peaks can be placed closely to each other. Hence, a quasi-broadband effect can be achieved.

This design technique can be used to potentially increase the operational frequency bandwidth and amplifying the peak displacement.

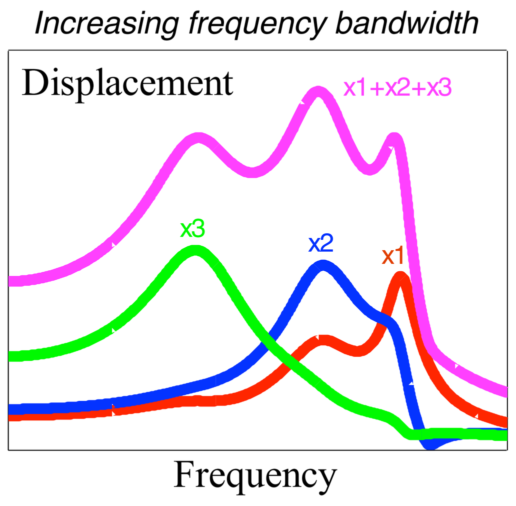
Equivalent mechanical model



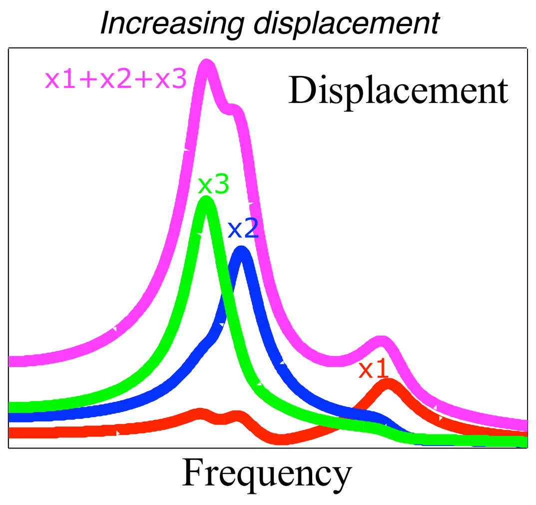
Governing equation:

$$[M]\ddot{X} + [C]\dot{X} + [K]X = F$$

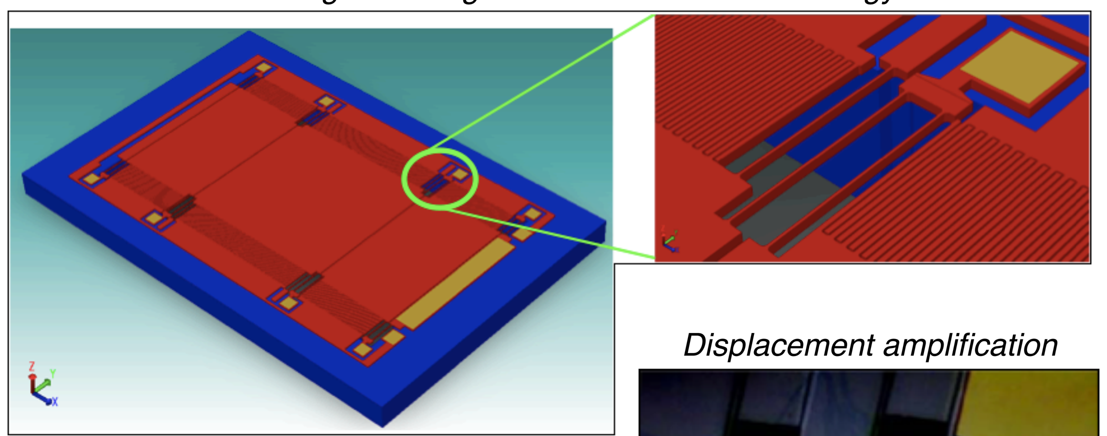
Increasing frequency bandwidth



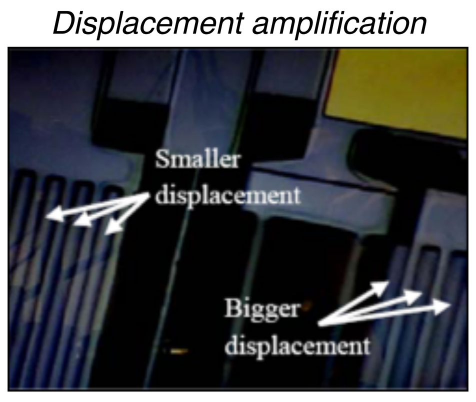
Increasing displacement



3D view of the designed 3 degree-of-freedom MEMS energy harvester

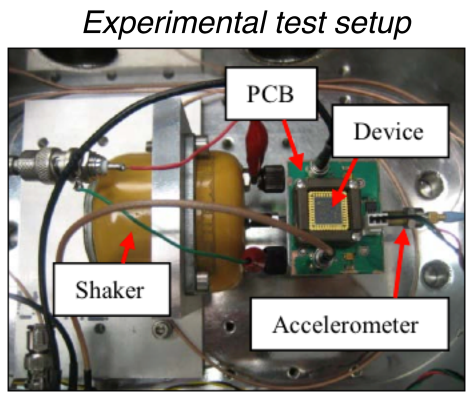


Displacement amplification



Method:
3-degree-of-freedom MEMS-based electrostatic energy harvester was fabricated using the standard SOI-MUMPS process. Testing and characterisation of devices at first resonant mode was carried out both in air and in vacuum.

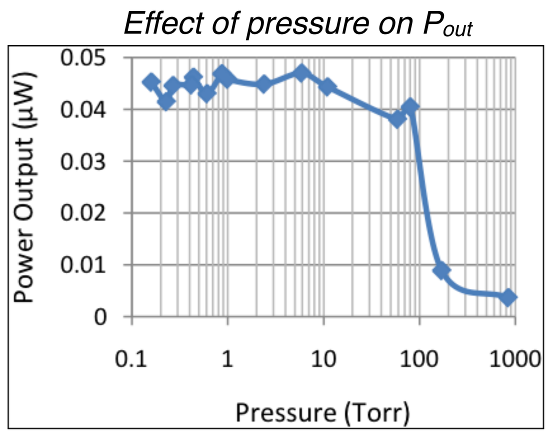
Experimental test setup



Result:
The maximum measured power output from the current device is 0.076 µW with peak voltage of 0.88 V, frequency of 14 kHz, input acceleration of 1.53 ms^{-2} and external load of 5.1 MΩ.

Power output P_{out} is directly proportional to the square of input acceleration and bias voltage. In terms of effect from pressure, there is a threshold below which the damping begins to drastically diminish. Thus, enabling larger vibration amplitudes.

Effect of pressure on P_{out}



Comparing the current device with selected electrostatic harvesters

Reference	Frequency (Hz)	Power (μW)	Power/Mass/Acceleration ($\mu W/g/ms^{-2}$)
Tashiro (2002)	6	36	0.046
Mitcheson (2004)	30	3.7	0.74
Arakawa (2004)	10	6	2.37
Despesse (2005)	50	1052	1.15
Ma (2005)	4200	0.065	0.42
Chiu (2007)	1870	1.2	1.85
This device (in air)	**1400**	**0.017**	**13.16**
This device (in vacuum)	**1430**	**0.113**	**87.97**

Literature cited

1. Wong, Z.J., Yan, J., Soga, K. and Seshia, A.A., (2009), A multi-degree-of-freedom electrostatic MEMS power harvester, *Proceedings of 9th International Workshop on Micro- and Nanotechnology for Power Generation and Energy Conversion Applications (PowerMEMS 2009)*, 1-4 Dec, Washington DC, USA, pp. 300-303.

2. Ye, G., Yan, J, Wong, Z.J., Soga, K and Seshia, A.A., (2009), Optimisation of a piezoelectric system for energy harvesting from traffic vibrations, *Proceedings of IEEE International Ultrasonics Symposium (IUS)*, 20-23 Sept, Rome, pp. 759-762

3. Ye, G. and Soga, K., (2011), Energy harvesting from water distribution systems, Department of Engineering, University of Cambridge, 30pp. (*to be published*)

Introduction

Motivation of energy harvesting: To enable sustainable self powered wireless sensor networks for structural health monitoring.

Ambient vibration harvesters:
- Suitable for integration into dark and enclosed systems.
- Vibration sources are ubiquitous. (The world is in a constant state of agitation.)

Micro-Electro-mechanical Systems (MEMS):
- Size miniaturisation.
- Integration with ICs.
- Low cost (when mass produced).

Issues:
- Narrow operational frequency band around resonance.
- Limited power density for feasible implementation.
- Lack of real vibration analytical models for system optimisation.
- Lack of studies on the feasibility in real world applications.

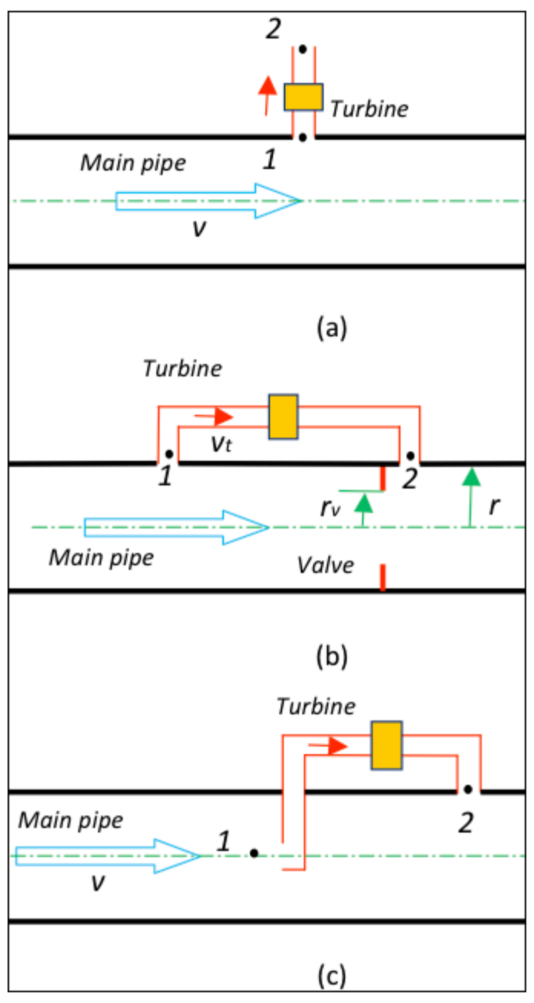
Energy harvesting for water distribution systems

Problem targeted: Feasibility study of employing energy harvesting to provide sustainable power supply for inaccessible wireless sensor nodes in water distribution systems.

Possible sources of energy:
(1) Hydraulic energy in bypass pipes.
(2) Hydrothermal energy in water-air temperature gradient.
(3) Kinetic energy from water pressure fluctuation.

Background research: The power consumption of a typical wireless hydraulic sensor node is at the order of 10's mW. While solar cells can generate sufficient power, they are not suitable for enclosed applications. Ambient vibration energy harvesting from manhole cover, even after the optimisation using the genetic algorithm, was still not enough to power the sensors.

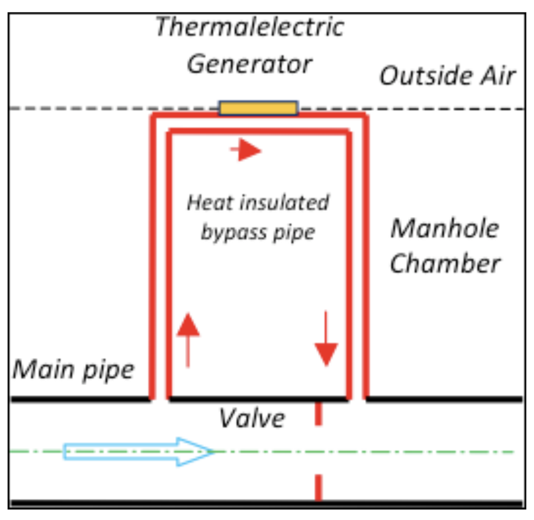
(1) Hydraulic energy harvester: Diverting water into bypass pipes to power microturbines. A pressure gradient is needed Three designs were investigated.



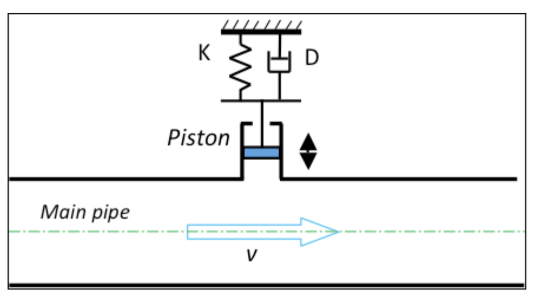
Bypass systems	Power
(a) Release water to the environment	144 – 196 W
(b) Flow driven by pressure drop after a valve	0.07 – 0.32 mW
(c) Flow driven by a Pitot tube	<1 μW

System (a) provides more than enough power. However, it wastes significant amount of water and causes severe disruption to the water distribution system. While (b) and (c) are inadequate to meet the power budget requirement.

(2) Hydrothermal energy harvester: A water bypass system was designed for this purpose (right). The mean water-air temperature gradient (North England) is around 3 °C. Using this value, a thermoelectric generator of size 40×40×4.2 mm can generate about 2.8 mW. An array of these generators can meet the power requirement.



(3) Water pressure fluctuation energy harvester: An electro-mechanical system (right) was designed, which harvests the kinetic energy from pressure fluctuation in the main pipe.



Genetic Algorithm was employed to optimise the design parameters of the harvester for real pressure fluctuation data. Numerical model demonstrated that such a system could ideally produce several $mWcm^{-2}$.

Conclusion: A feasibility study utilising fundamental modelling and analysis was carried out. The hydrothermal and water pressure fluctuation energy harvesters appear to yield promising results. Future work will be focused on the experimental testing and further analysis of these two proposed systems.

Acknowledgement

Research funding from the Engineering and Physical Sciences Research Council (EPSRC) for the Underground M3 project and the NEPTUNE project.

Optimisation for real vibration sources

Problem targeted: Lack of analytical models to describe real vibration sources. Most researches simply employ sinusoidal time domain acceleration as vibration input.

Proposed solution: A genetic algorithm with numerical simulations that considers the effects of each parameter of the real vibration input to produce an optimal frequency response. A piezoelectric cantilever system was optimised for experimental acceleration data from the vibrations of a vehicle excited manhole.

Modelling piezoelectric cantilever energy harvester:

Equation (3) is the output power when the system operates at a specific resonant frequency. However, real vibrations are broadband in nature.

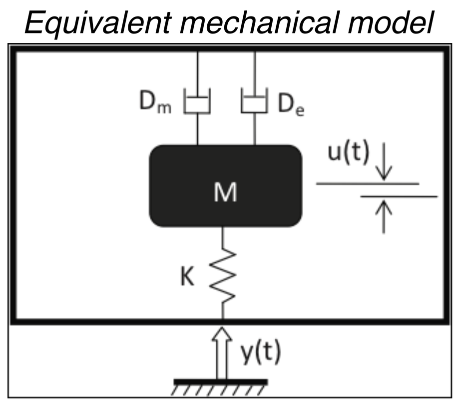
$$M\ddot{u}(t) + D\dot{u}(t) + Ku(t) + Av(t) = -M\ddot{y}(t) \quad (1)$$

$$v(t) = RA\dot{u}(t) - RC\dot{v}(t) \quad (2)$$

$$p = \frac{RM^2A^2\omega^4}{2[(A^2R+D)^2 + (RCD\omega)^2]}y^2 \quad (3)$$

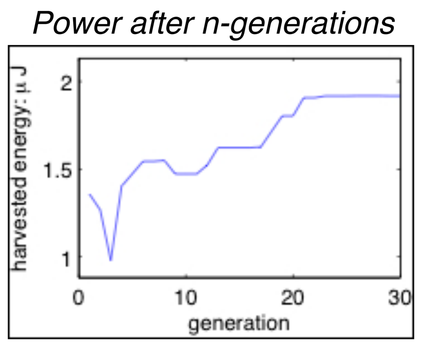
M - proof mass
D_M - mechanical damping
D_E - electrical damping
D - total damping
K - spring stiffness
A - piezoelectric coefficient
R - resistive load
C - capacitance of piezoelectric material
$u(t)$ - displacement
$y(t)$ - excitation displacement
$v(t)$ - output voltage
p - output power
ω - natural frequency

Equivalent mechanical model



Method: Initially, a trial point is selected for each parameter and is then iteratively optimised. Roulette wheel selection is used to reproduce new generation of populations. Result converges to an optimum design with maximum energy output after n-generations.

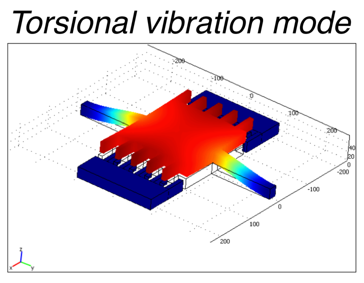
Power after n-generations



Result: Experimental testing has shown significant enhancement in energy harvested from the design optimised by the genetic algorithm than sinusoidal simulations. This technique is promising for optimising harvesters aimed at practical applications.

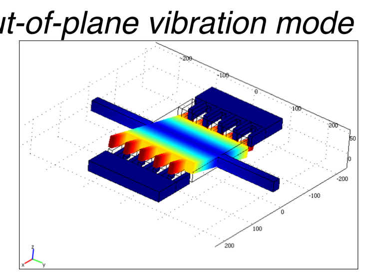
Novel design improvements

Torsional vibration mode

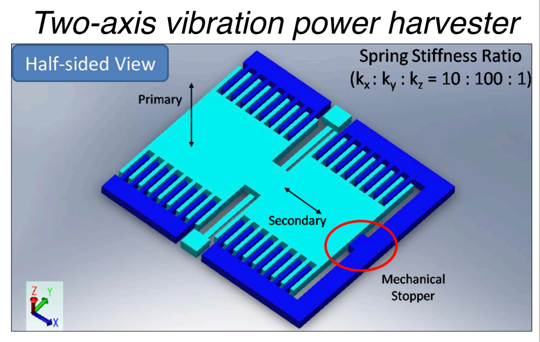


Advantages
- Large ΔC without displacement limit.
- Allow compact placing of comb fingers. Thus, increases power density.

Out-of-plane vibration mode

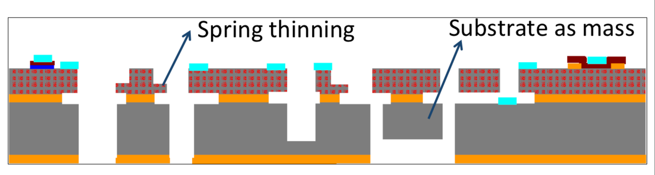


Two-axis vibration power harvester



Advantages
- Simultaneous energy harvesting in x & z directions.
- Mechanical stopper to limit unexpectedly large vibration in real-world engineering structures.

Development of new micro-fabrication process on SOI wafer
(collaboration with National Research Council, Italy)



- To fabricate more complicated structures for higher performance.
- To enable device & circuits integration.

Future work

- MEMS design improvement.
- Investigate novel methods to maximise the power density and increase operational bandwidth.
  - Wide band
  - Random vibration
  - Mechanical amplifier
  - Multi-axial
  - Coupled harvesters
- Device design for various energy sources and real applications.
- Power circuit design and system integration.
- Test equipment setup to model real vibrations.

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