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Broadband Vibration Energy Harvesting

Frequency tuning and bistable solutions

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Energy Harvesting 2015
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Overview

- Motivation
- Frequency Tuning
  - Basics
  - Mechanical tuning method
  - Electrical tuning method
  - Performance of linear energy harvesters under multiple-peak excitations
- Coupled Bistable Structures for Energy Harvesting Applications
  - Principle
  - Coupled bistable vibration energy harvesters
- Conclusions

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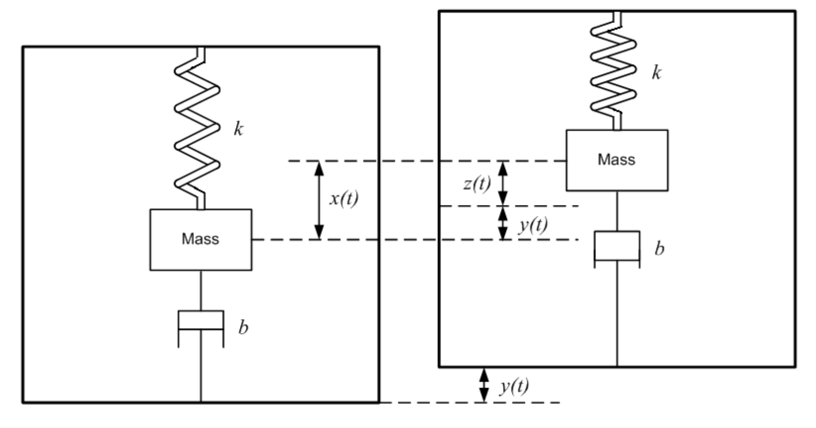
Motivation

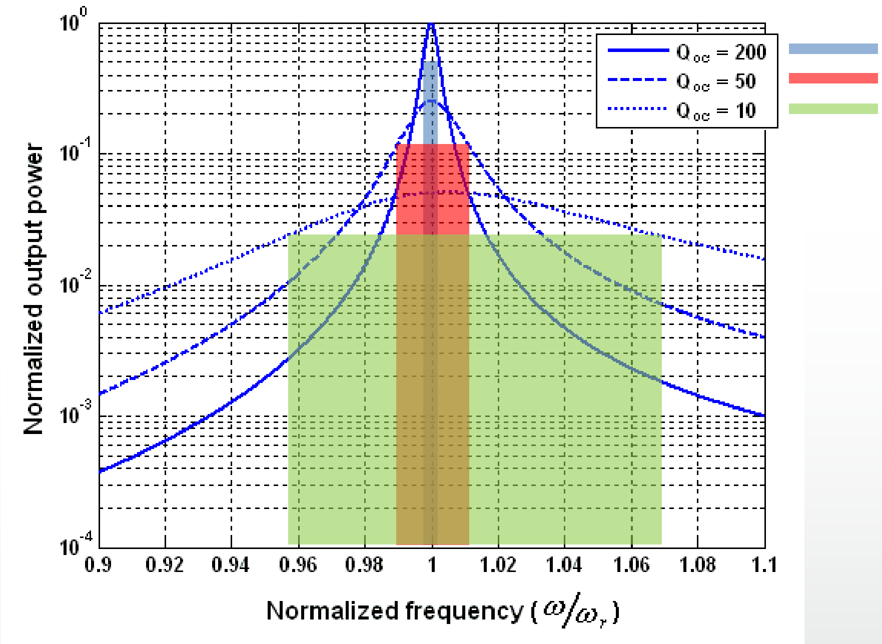
Motivation

A linear vibration energy harvesters can be modelled as a spring-mass-damper system.



$$m \cdot \frac{d^2 z(t)}{dt^2} + b \cdot \frac{dz(t)}{dt} + k \cdot z(t) = -m \cdot \frac{d^2 y(t)}{dt^2}$$

$$P = \frac{m \zeta_T Y^2 \left(\frac{\omega}{\omega_r}\right)^3 \omega^3}{\left[1 - \left(\frac{\omega}{\omega_r}\right)^2\right]^2 + \left[2\zeta_T \frac{\omega}{\omega_r}\right]^2}$$



Maximum power is generated only when resonant frequency matches ambient vibration frequency.

Motivation

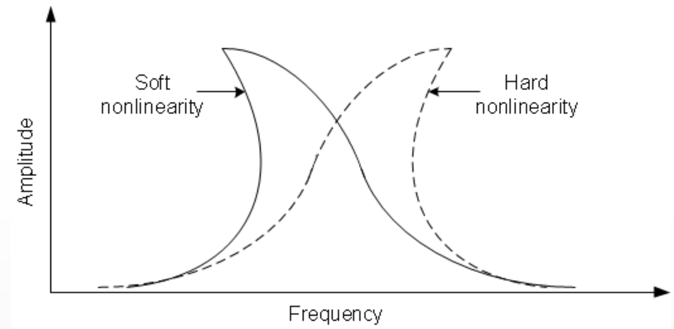
Motivation: to increase operational bandwidth of vibration energy harvesters:

- Resonant frequency tuning

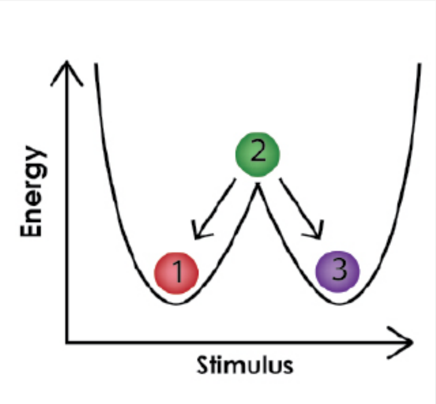
$$f_{\text{resonant}} = f_{\text{vibration}}$$

Mechanical/electrical methods

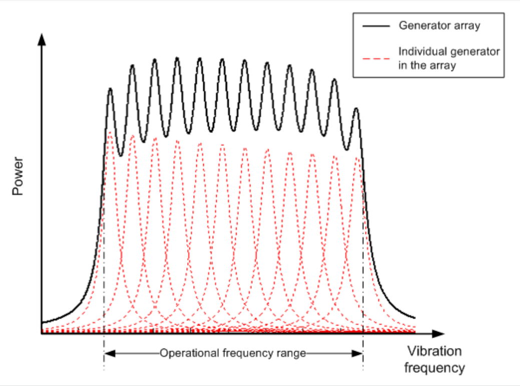
- Duffing's nonlinear structure



- Bistable structure



- Harvester array



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Frequency Tuning

Basics

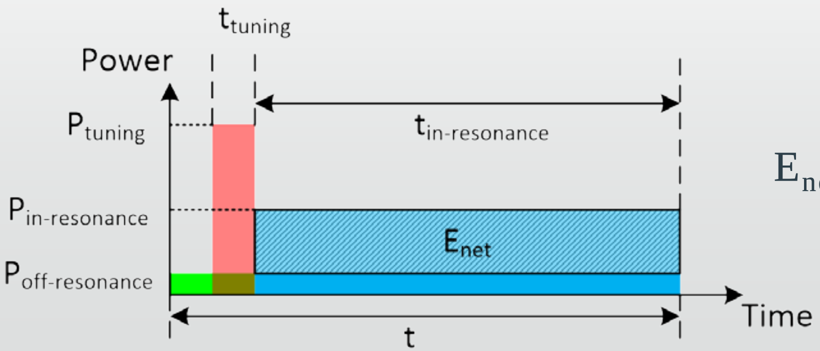
Passive and Active Frequency Tuning

- Passive frequency tuning methods do not require extra energy but are uncontrollable.

- Active frequency tuning methods require extra energy. Closed-loop control schemes can be applied to enable automatic and accurate frequency tracking.
  - Mechanical methods: Tuning by altering mechanical properties.
  - Electrical methods: Tuning by altering electrical damping.

Intermittent and Continuous Tuning

- Intermittent tuning: Energy is consumed periodically to tune the frequency.
- Continuous tuning: The tuning mechanism is continuously powered.
- Intermittent tuning is more efficient.
  - It is turned off when the harvester works at the right frequency.
  - Producing a positive net output energy is more probable.



$$E_{net} = P_{in\text{-}resonance} \cdot t_{in\text{-}resonance} - P_{in\text{-}resonance} \cdot t > P_{tuning} \cdot t_{tuning}$$

Evaluation of Tuning Methods

- The energy consumed by the tuning mechanism should be as small as possible and must not exceed the energy produced by the energy harvester.
- The tuning mechanism should achieve a sufficient operational frequency range.
- The tuning mechanism should achieve a suitable degree of frequency resolution.
- The tuning mechanism applied should not increase the damping within the effective tuning range.
- The tuning mechanism should be applicable to automatic frequency tracking.

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Frequency Tuning

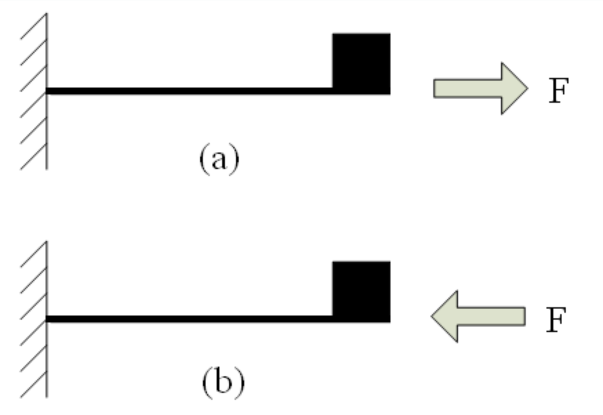
Mechanical tuning method

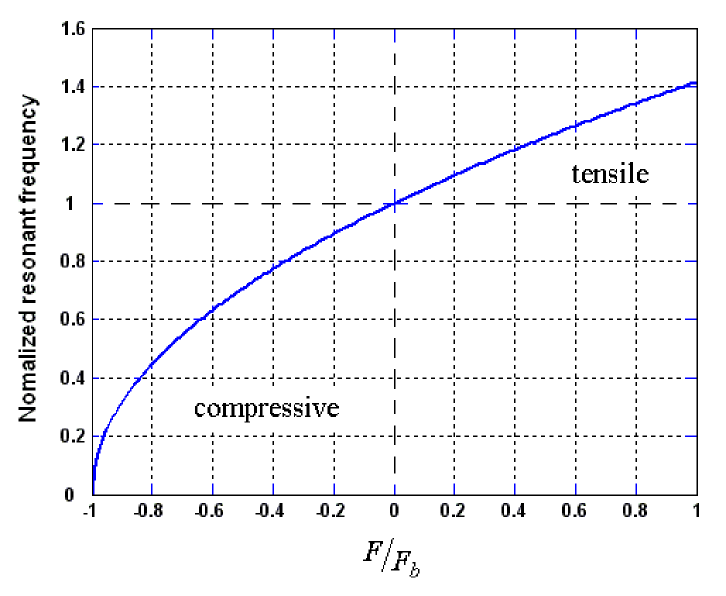
Principle

For a cantilever based energy harvester operating in the fundamental flexural mode (mode 1); its resonant frequency an axial load, f_{r1}', is given by:

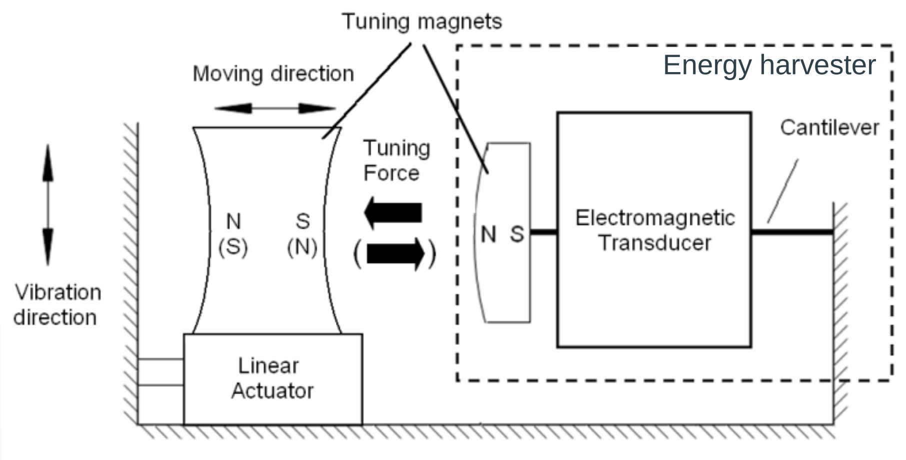
$$f_{r1}' = f_{r1} \cdot \sqrt{1 + \frac{F}{F_b}}$$

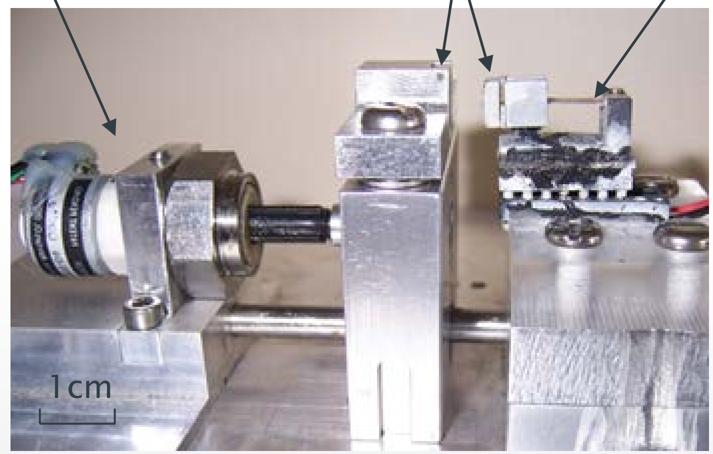
F : axial load
F_b: buckling force





A Tunable Vibration Energy Harvester

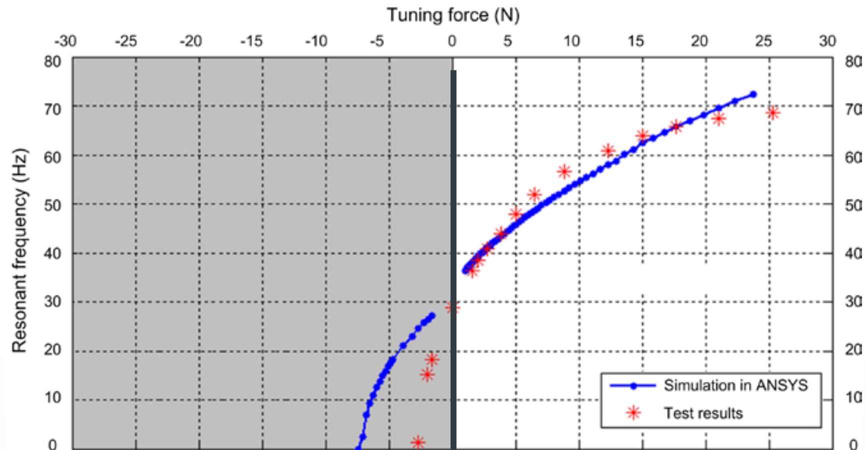




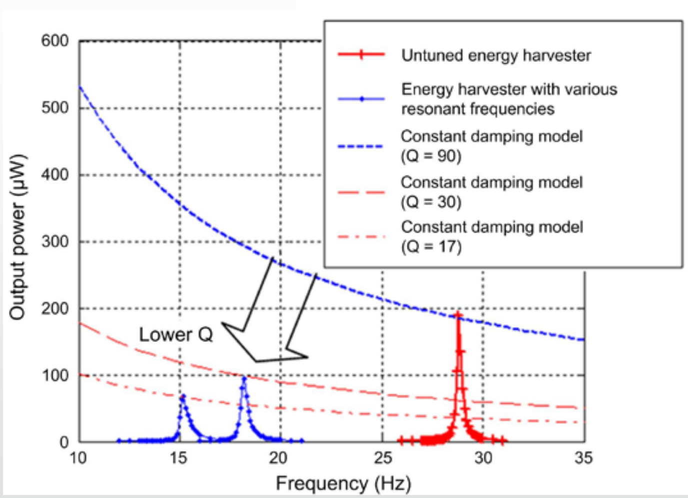
- Contactless (magnetic) force is applied.
- A linear actuator is used to adjust the position of the tuning magnet, thus the tuning force.

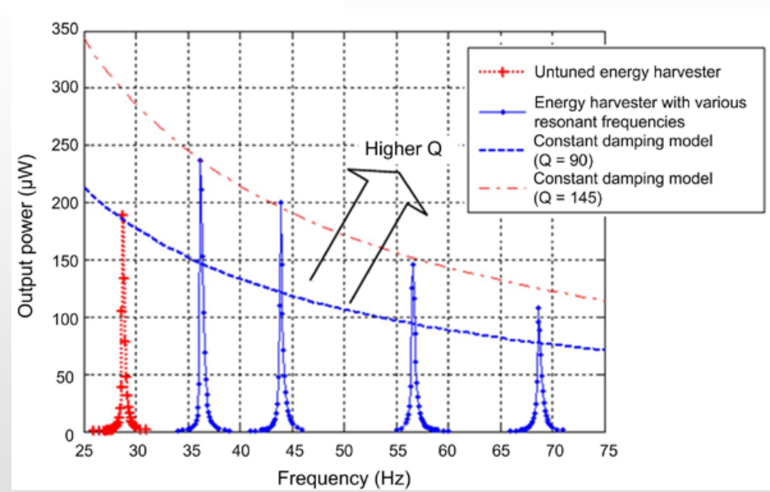
Experimental Results

Compressive force



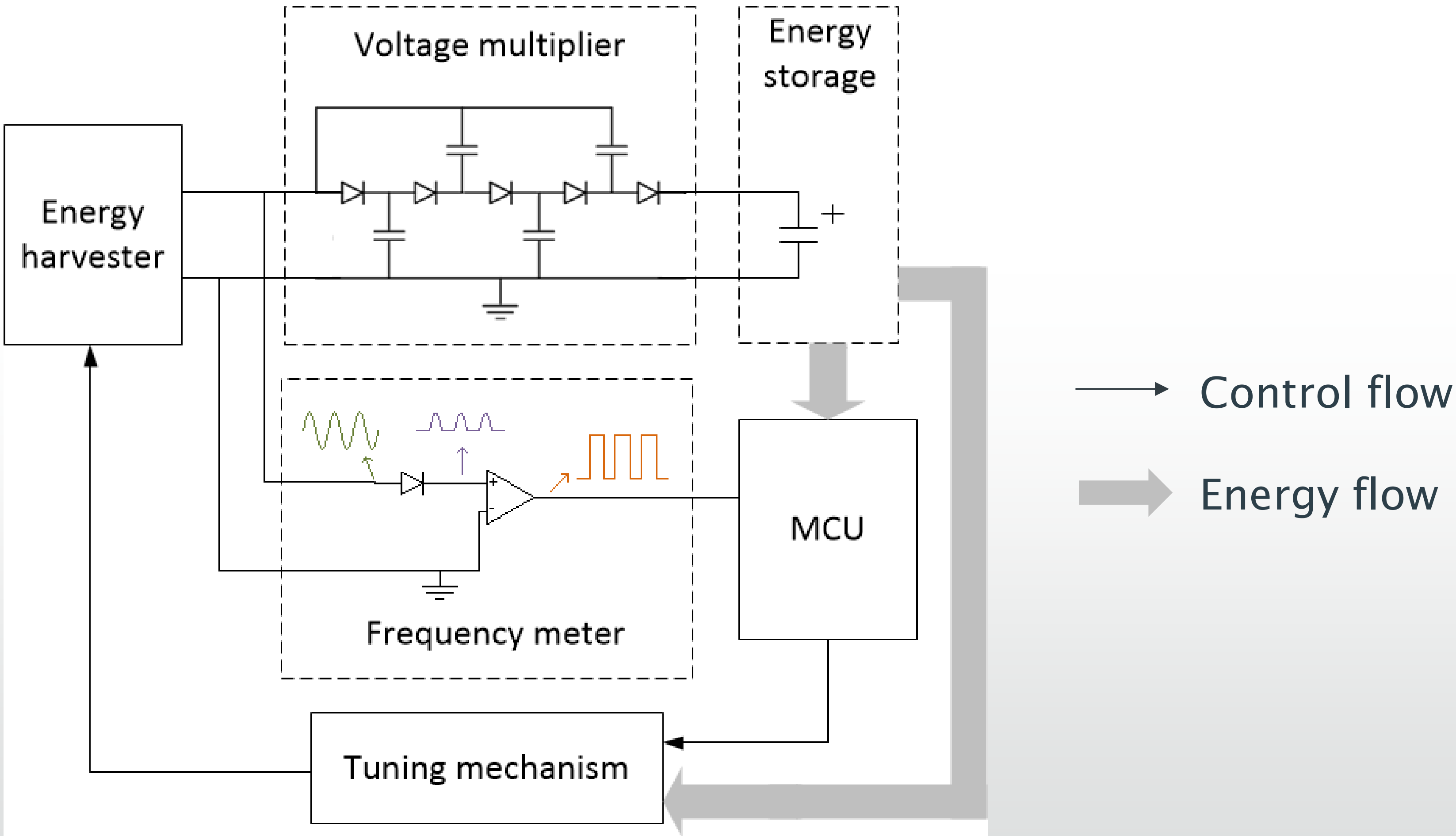
Tensile force



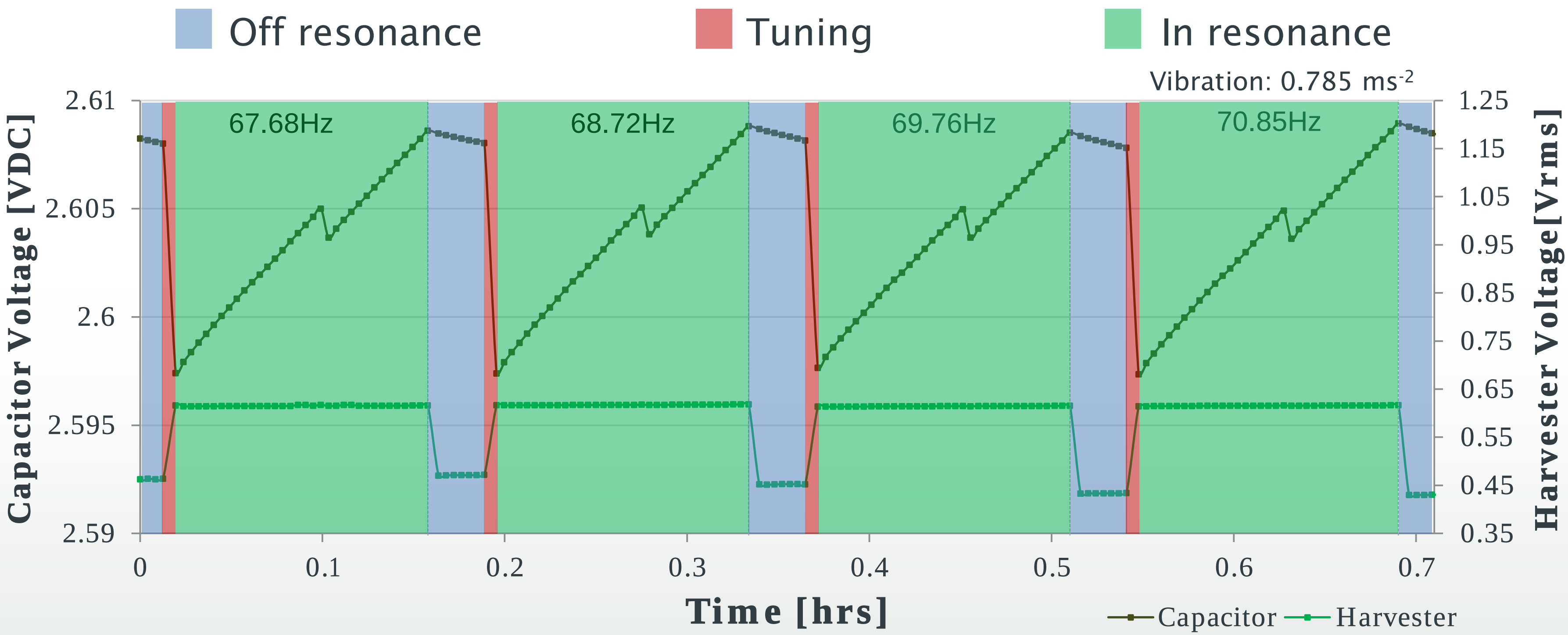


- Compressive forces increase damping while tensile forces reduces damping.

Closed-loop Frequency Tuning



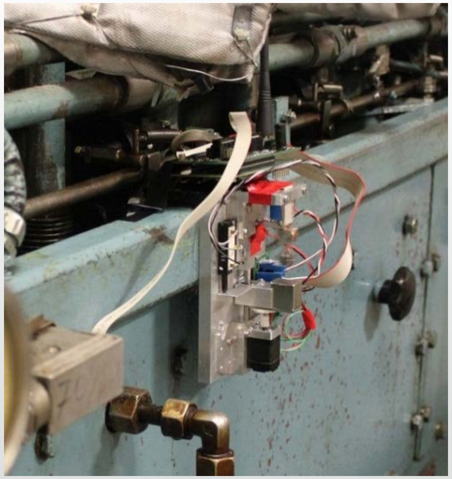
Closed-loop Frequency Tuning



- Frequency shifts ~1Hz
- Harvester's voltage drops when off-resonance
- MCU wakes from sleep every 320 seconds

Case Study

A Red Funnel ferry running between Southampton and Isle of Wight

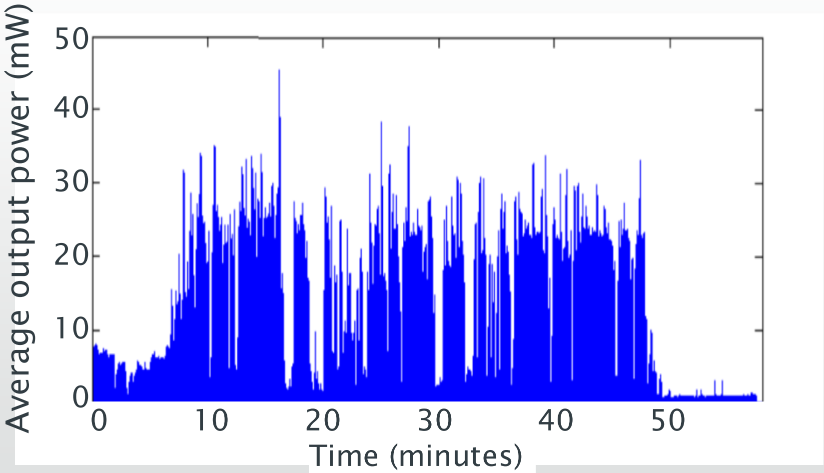


A tunable vibration energy harvester powering wireless sensors on a Red Funnel ferry

Typical vibration on the engine

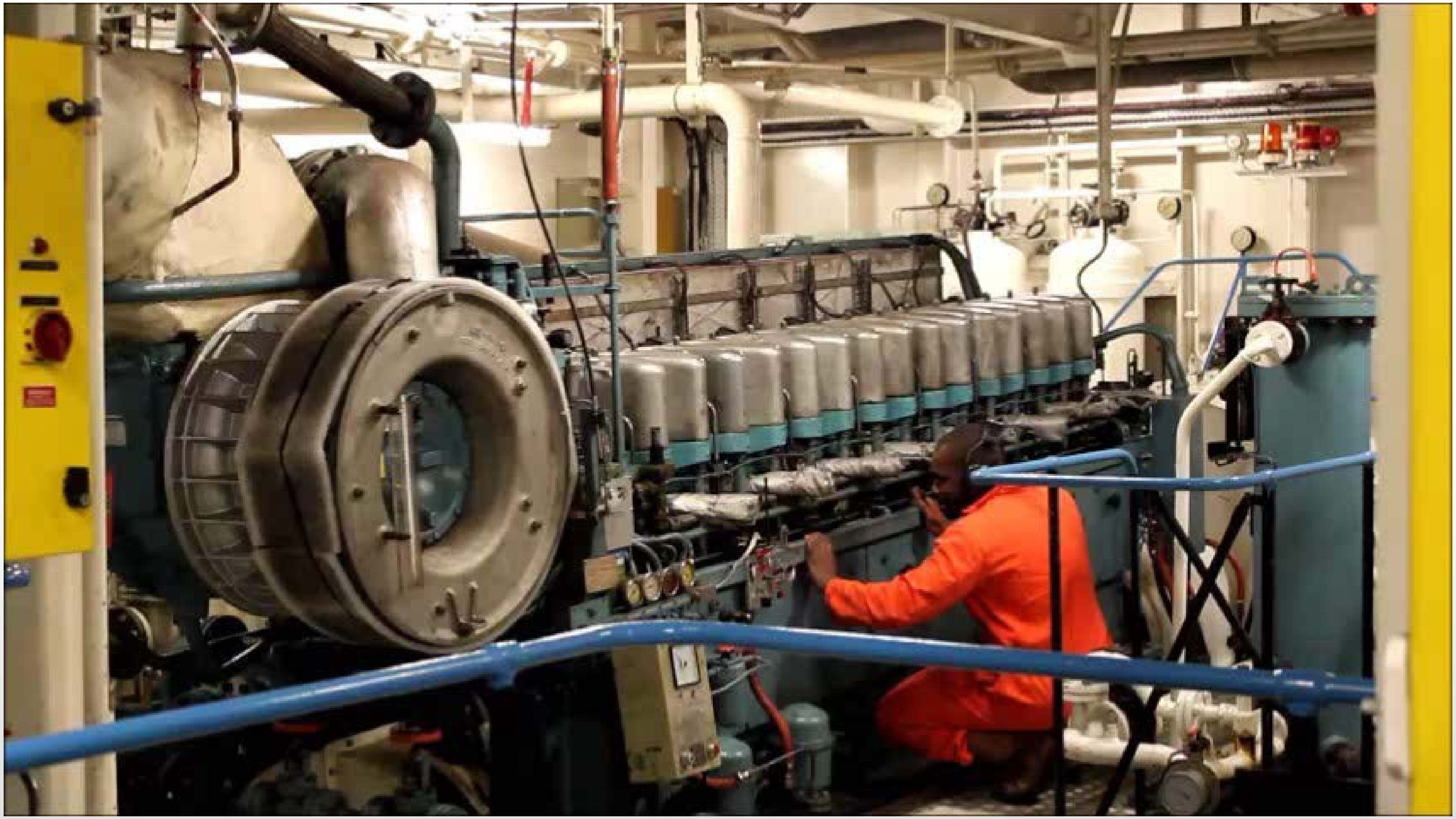
Normal speed (~715RPM)		Fast speed (~750RPM)	
f (Hz)	Ampl. (m$\boldsymbol{g}_{pk}$)	*f* (Hz)	Ampl. (m$\boldsymbol{g}_{pk}$)
47-48 Hz	700 - 950	~50	450

Frequency tuning range of the energy harvester: 42 – 55 Hz



Real-time output power of the harvester during one crossing

Case Study



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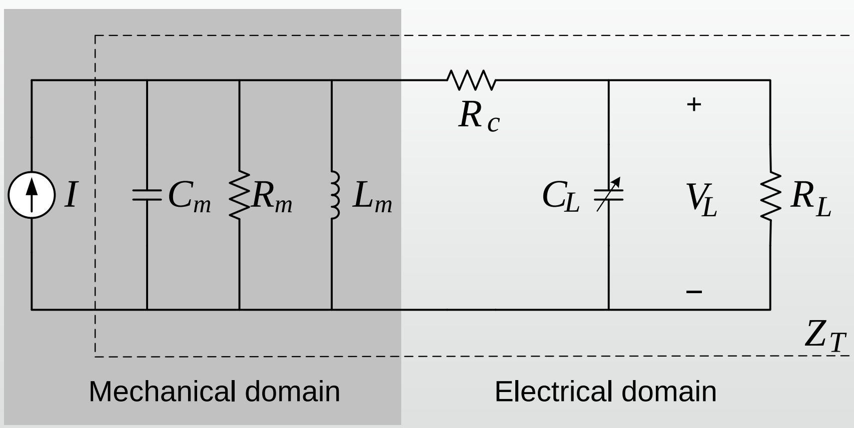
Frequency Tuning

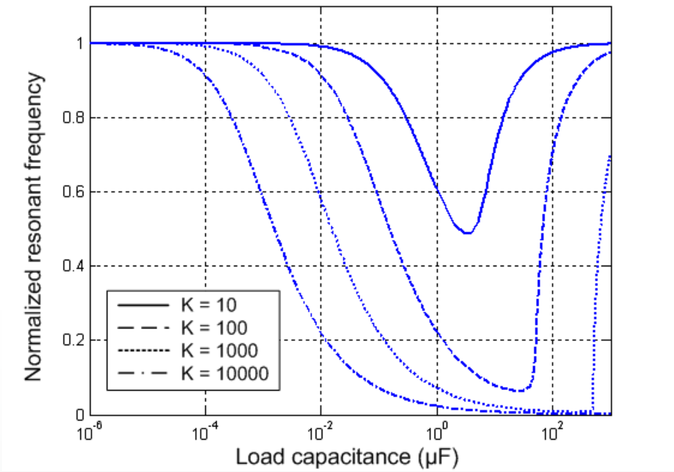
Electrical tuning method

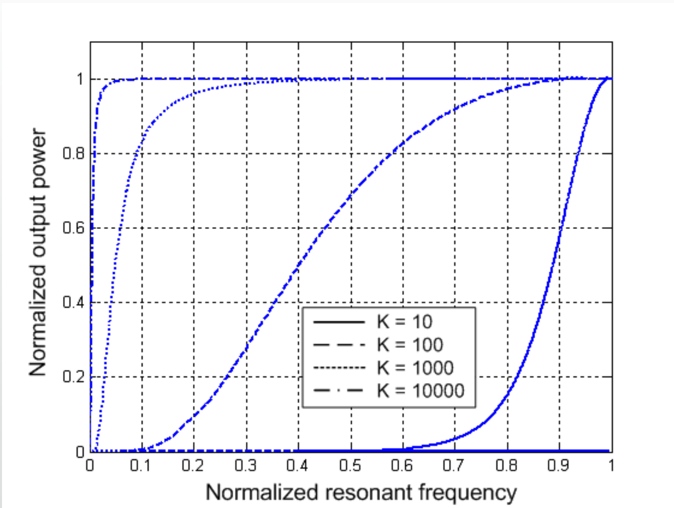
Principle

- The basic principle of electrical tuning is to change the electrical damping by adjusting the electrical load (*R*, *L*, *C*), which causes the power spectrum of the energy harvester to shift.
- Strong electromechanical coupling is required to achieve large frequency range.

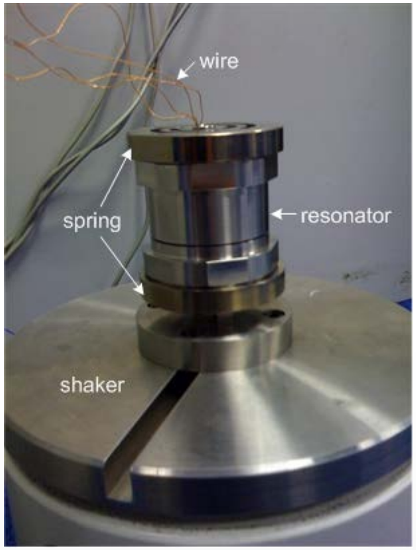


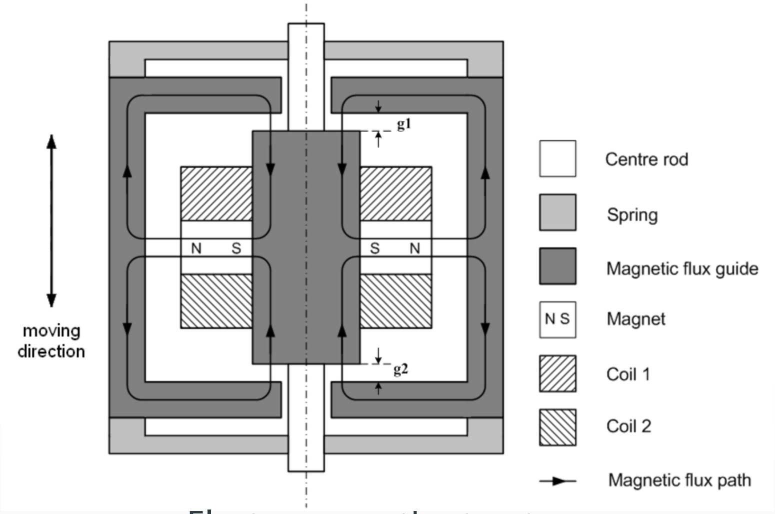
Equivalent circuit of an electrically tunable vibration energy harvester





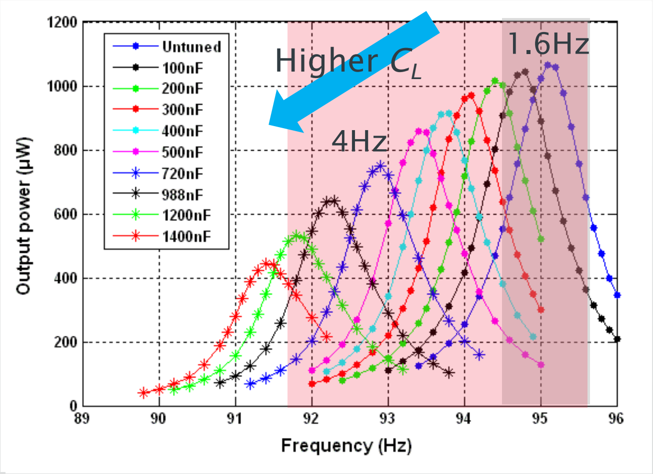
An Electrically Tunable Vibration Energy Harvester





Electromagnetic structure

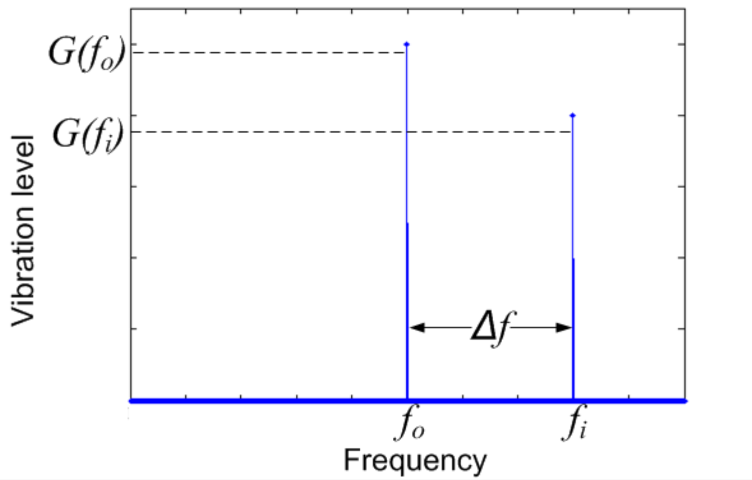
Excitation level:
10m*G*



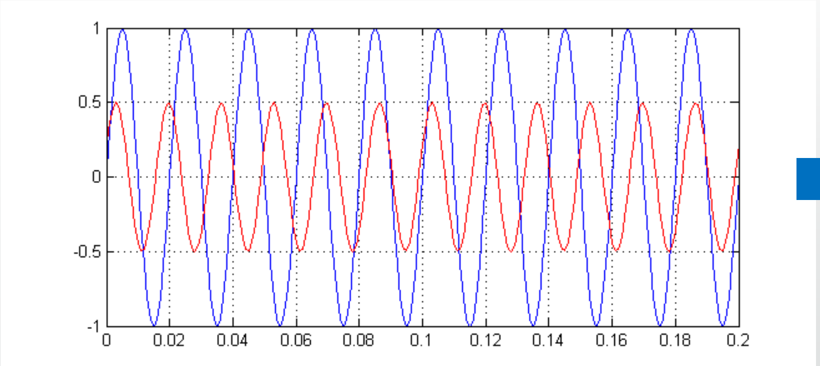
Frequency Tuning

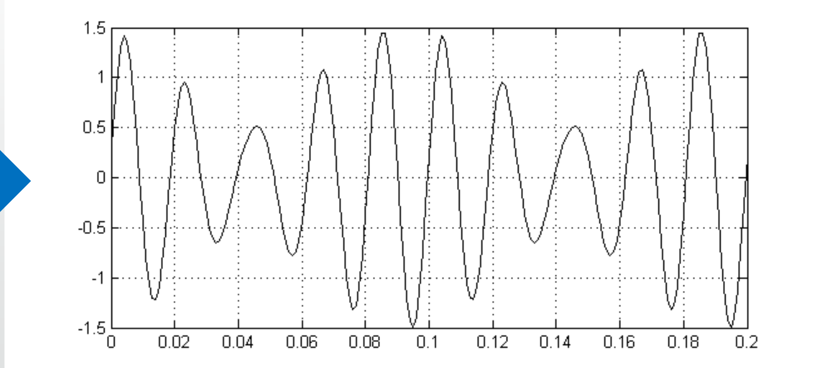
Performance of linear energy harvesters under multiple-peak excitations

Multiple-peak Excitations



- Main peak: f_o, $G(f_0)$
- Interference peak: f_i, $G(f_i)$



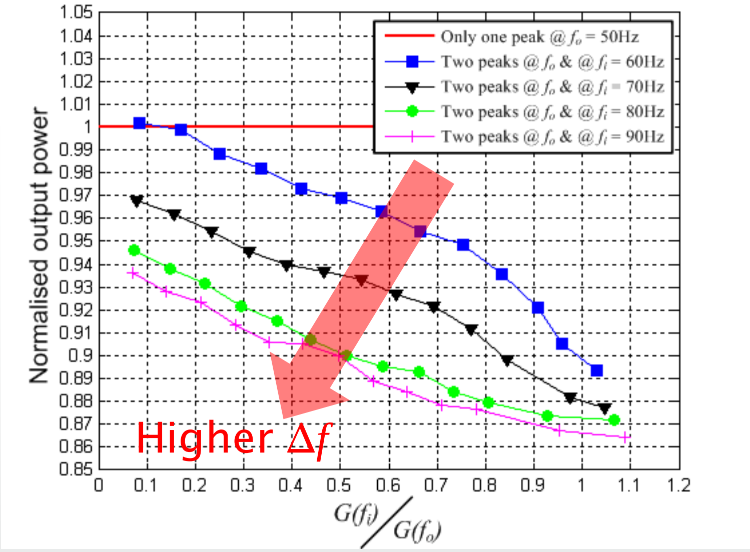


Main signal
Interference signal

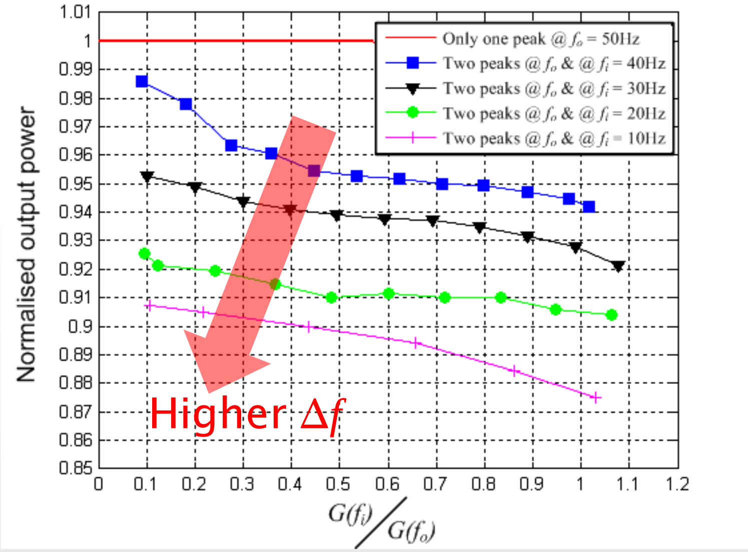
Combined signal

Performance of Linear Energy Harvesters under Multiple-peak Excitations

$f_i > f_o$



$f_i < f_o$



Output power drops as

- Frequency difference increases
- Amplitude of the interference peak increases

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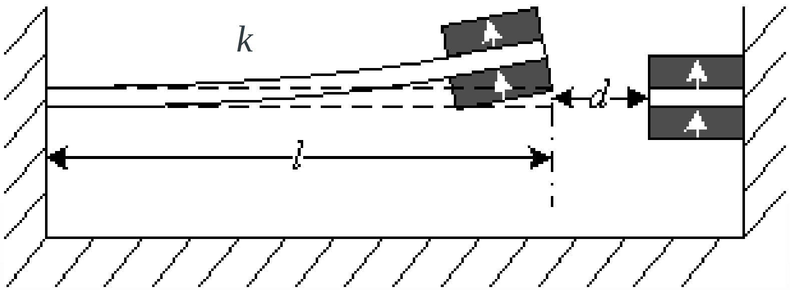
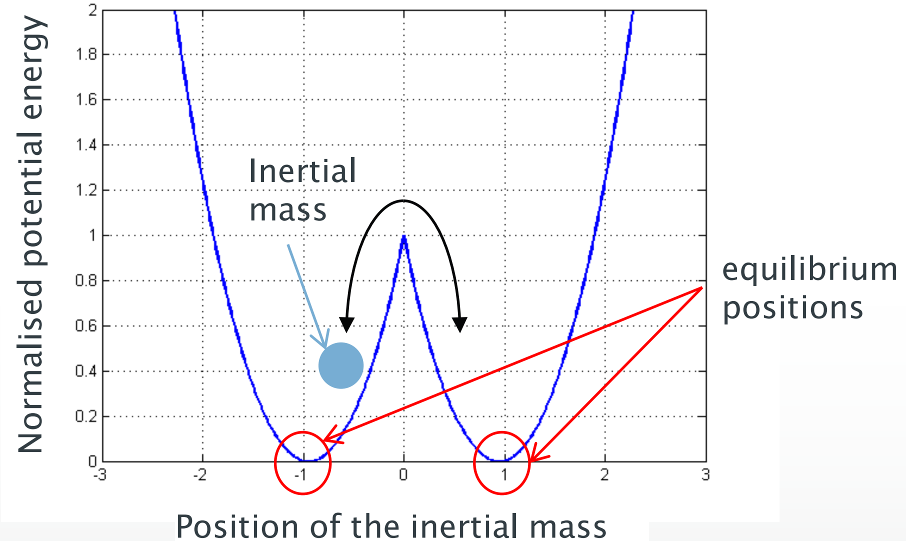
Coupled Bistable Structures for Energy Harvesting Applications

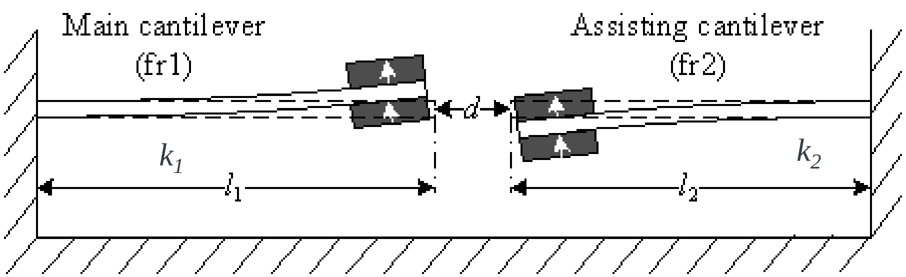
Conventional Bistable Structures

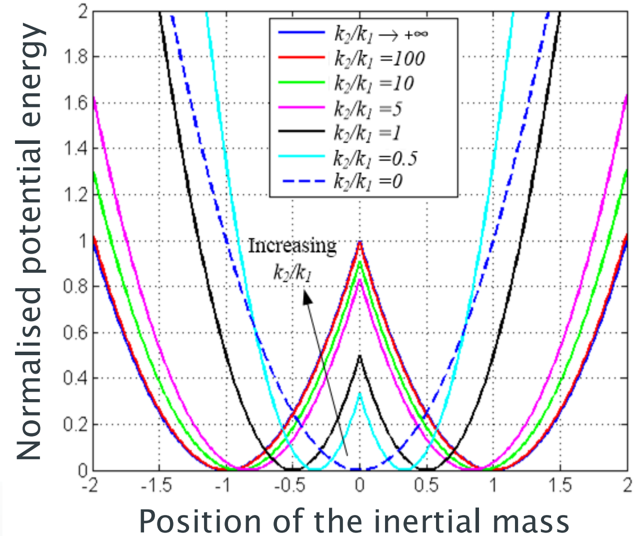




- It consists of a cantilever with a magnet at the tip and a fixed magnet.
- Repelling force between the two magnets.
- Inertial mass jumps between two equilibrium positions.
- Bistable vibration energy harvesters have better performance under wideband excitation compared to a linear harvester.
- It requires great excitation level to trigger bistable operation.

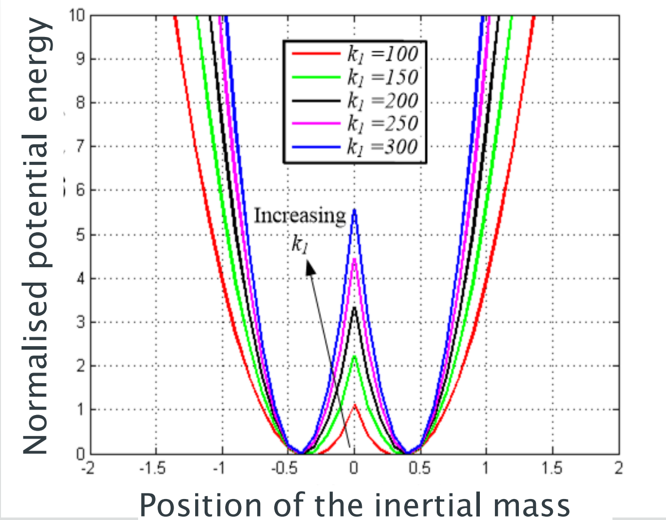
Coupled Bistable Structures



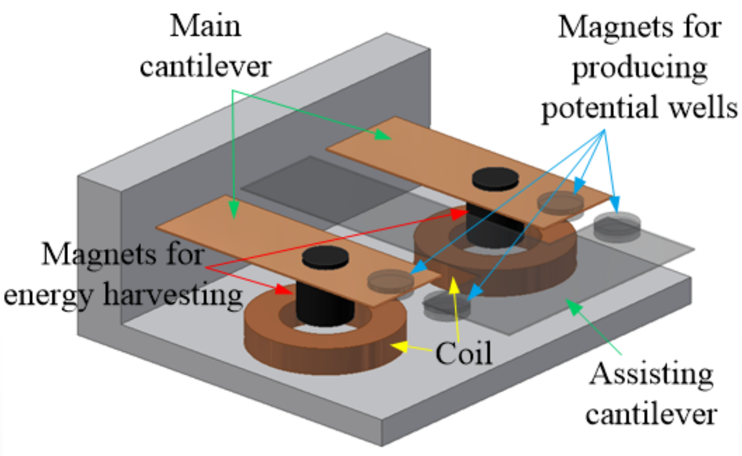


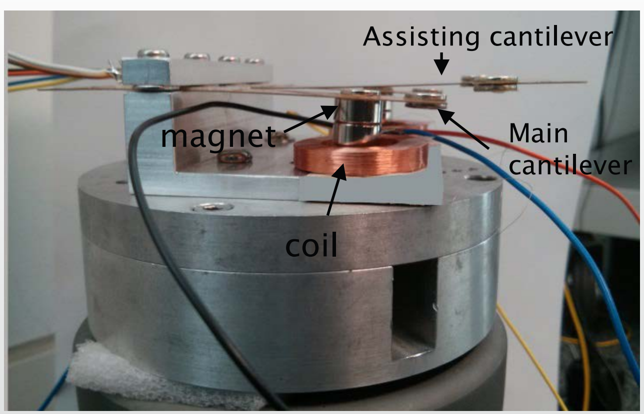
- The coupled bistable structure requires lower excitation to trigger the bistable operation.

- It is preferred that the resonant frequency of the assisting cantilever is lower than that of the main cantilever ($k_2 < k_1$).



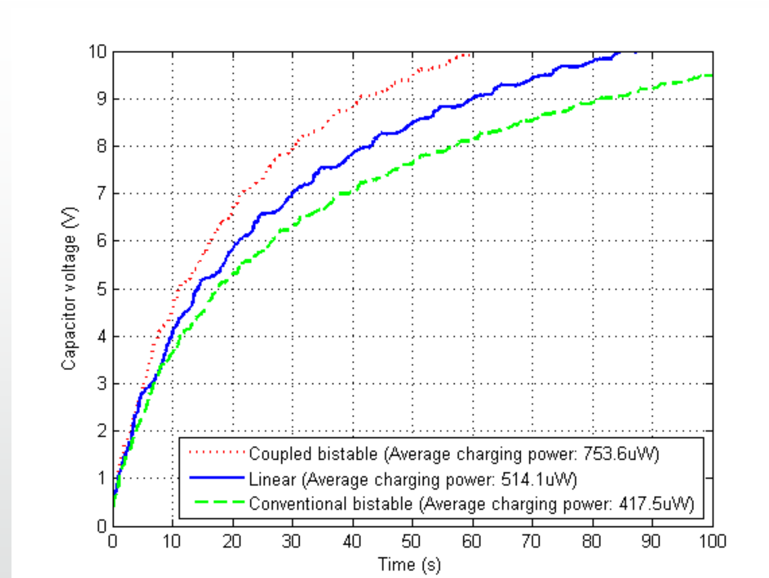
Coupled Bistable Energy Harvester 1





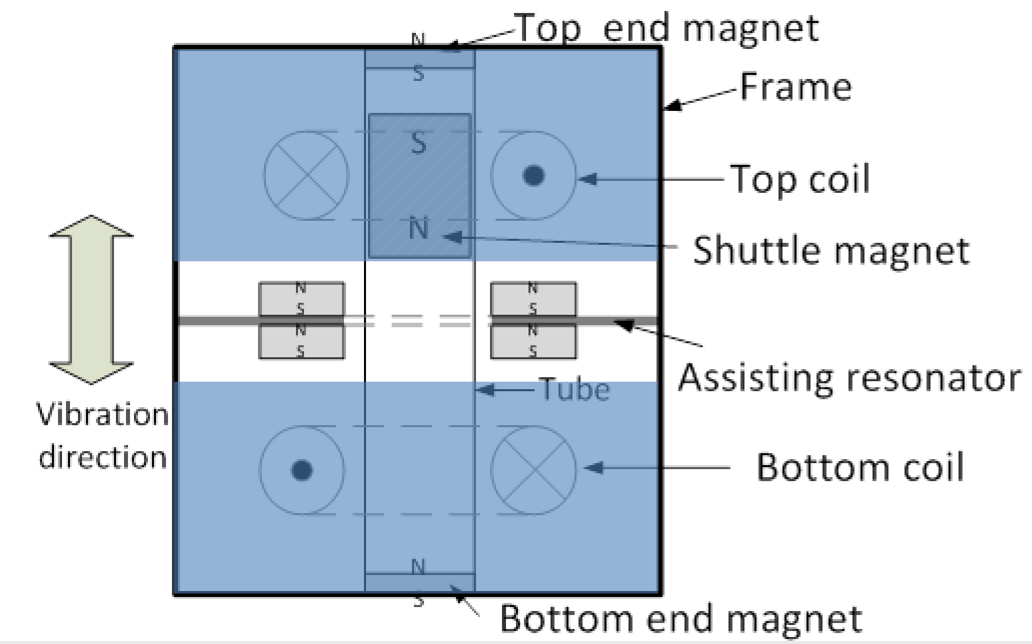
Electromagnetic energy harvester with a couple bistable structure

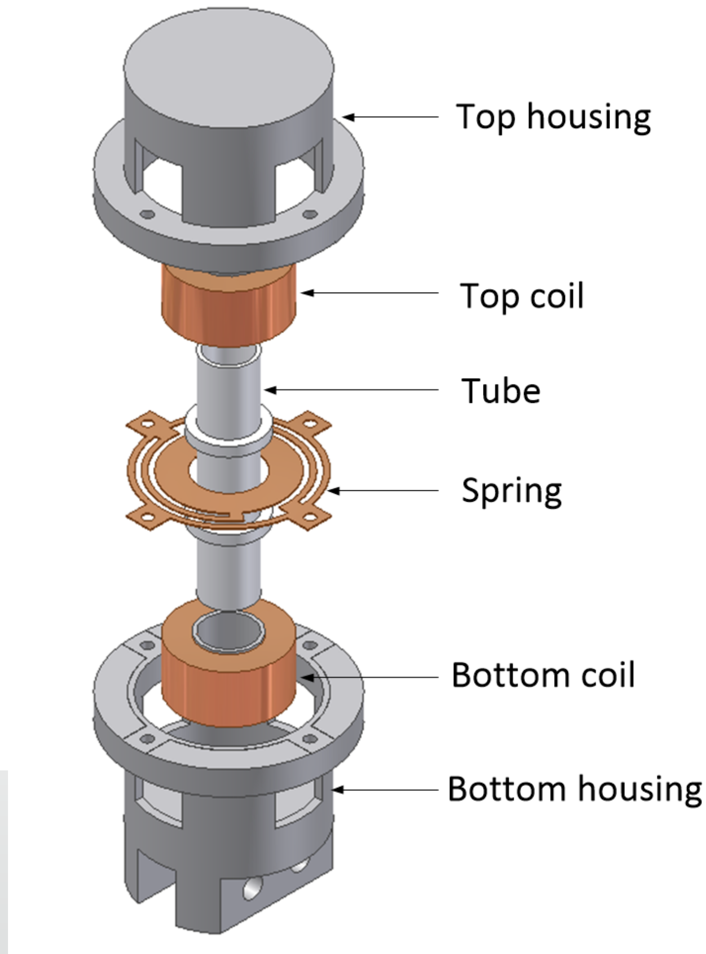
- Main cantilevers: 28.9 Hz
- Assisting cantilever: 16 Hz



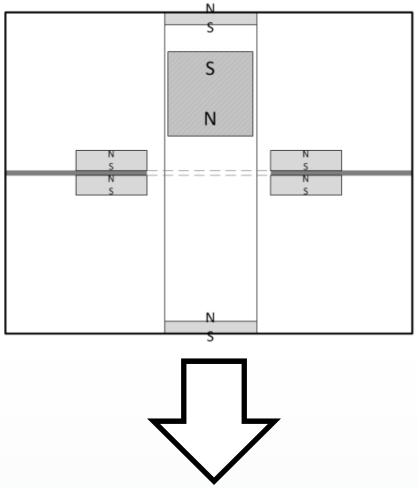
Comparison of charging rate under white noise excitation

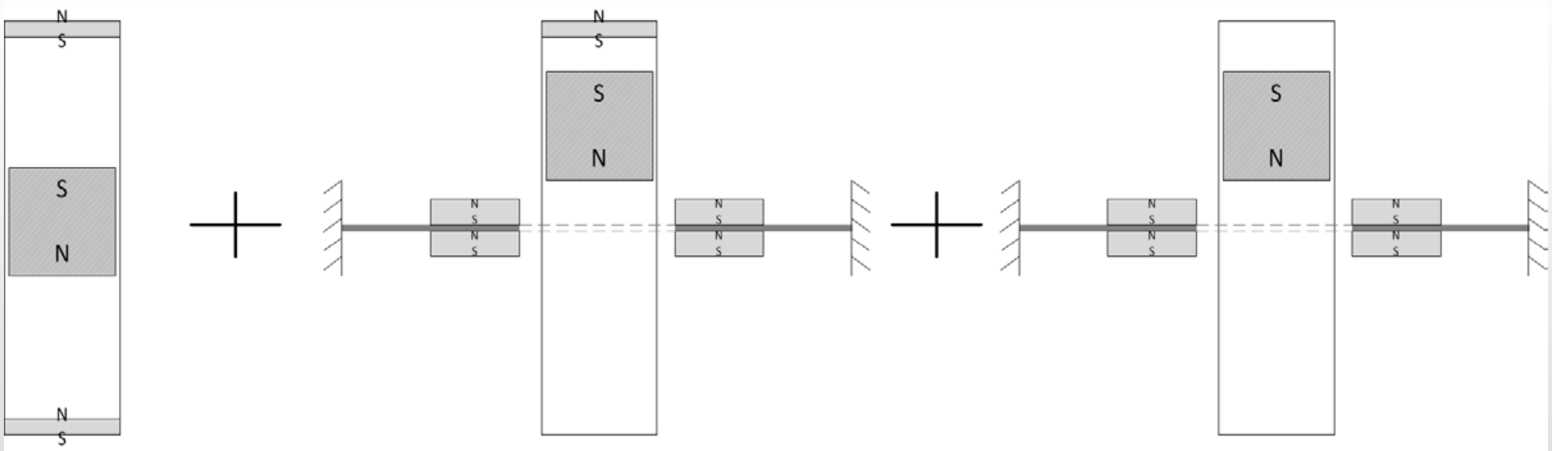
Coupled Bistable Energy Harvester 2





Coupled Bistable Energy Harvester 2



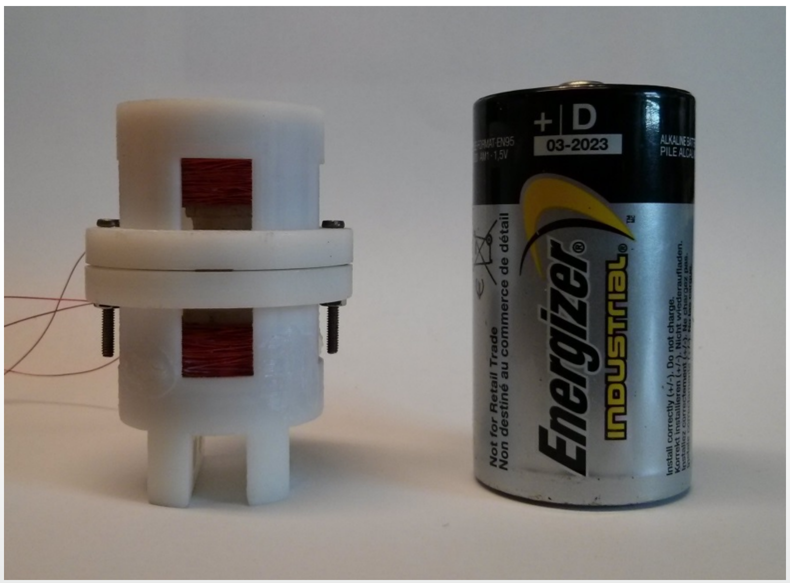


Nonlinear structure
(top and bottom magnets)

Nonlinear structure
(middle and bottom/top magnets)

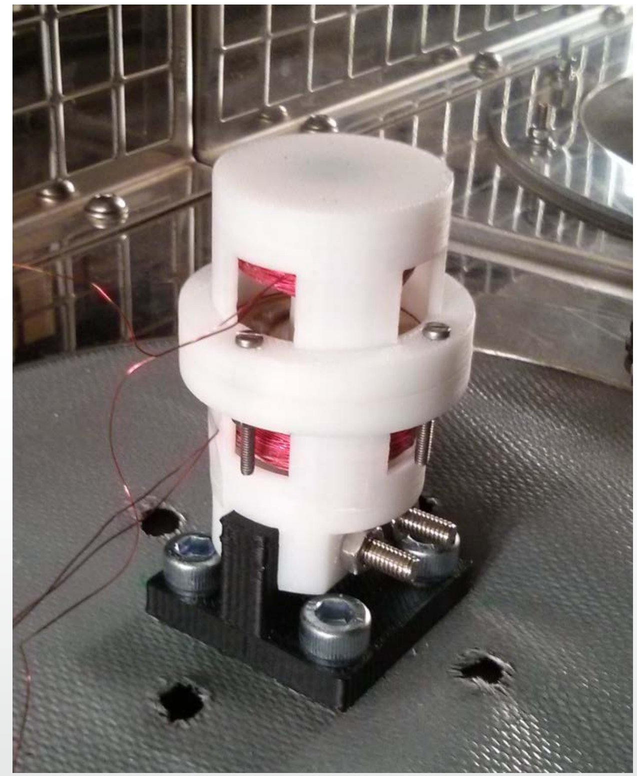
Linear resonator*
(coil spring)

Assembled Harvester



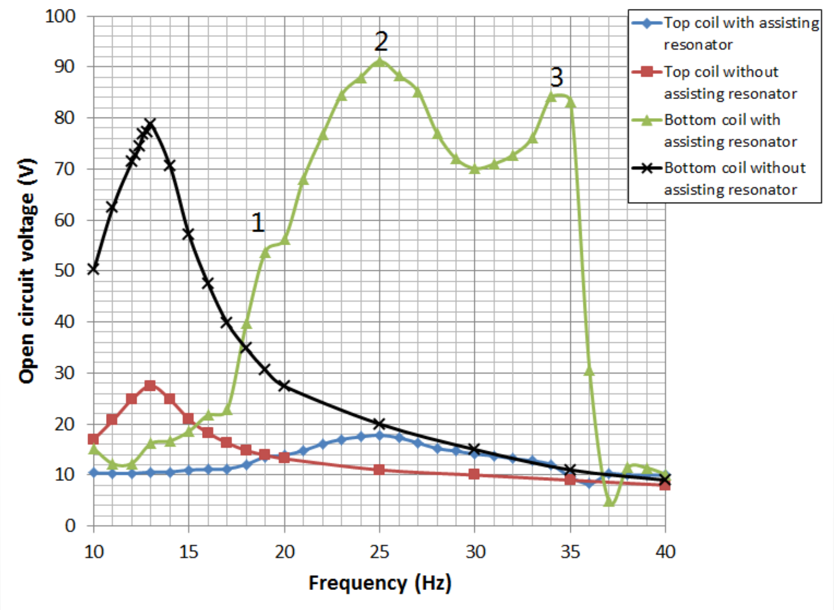
Harvester D-battery

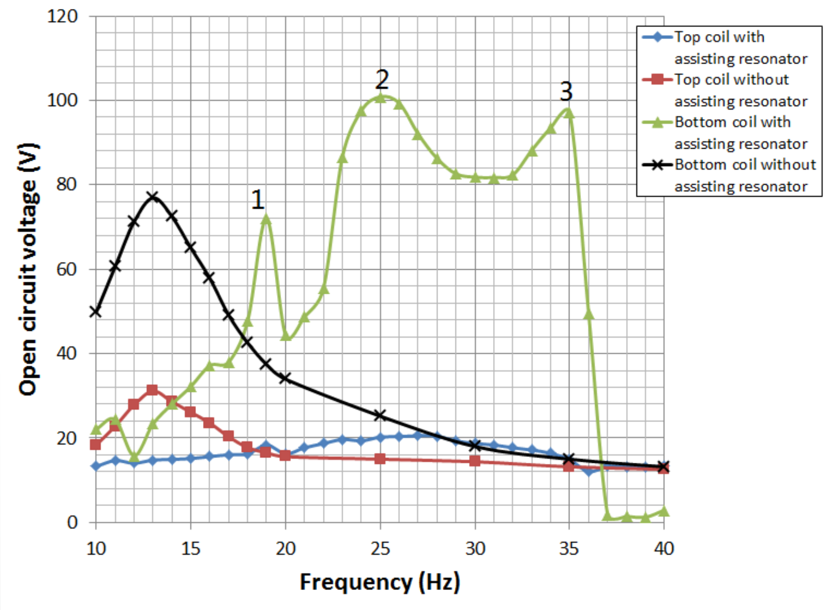
Diameter: 40 mm
Length: 56 mm (including the mounting section)



Harvester mounted on the shaker

Results

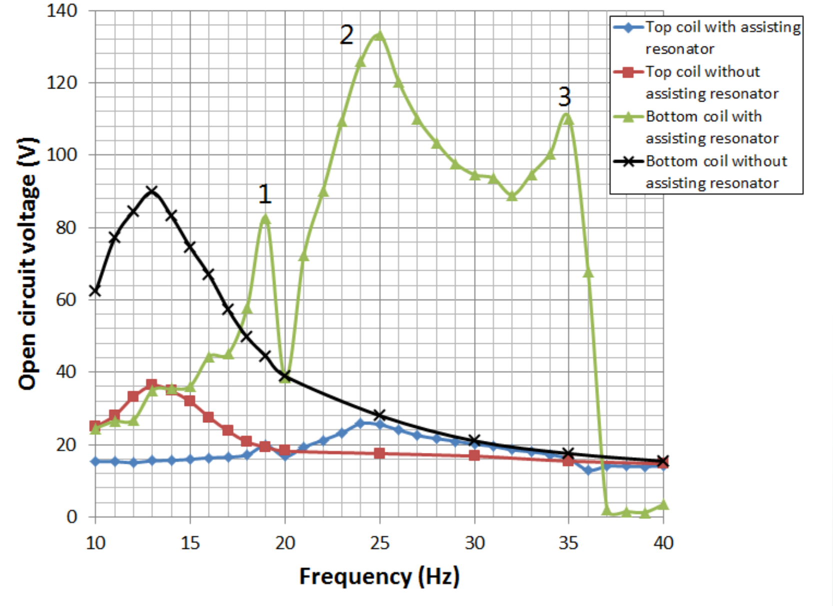




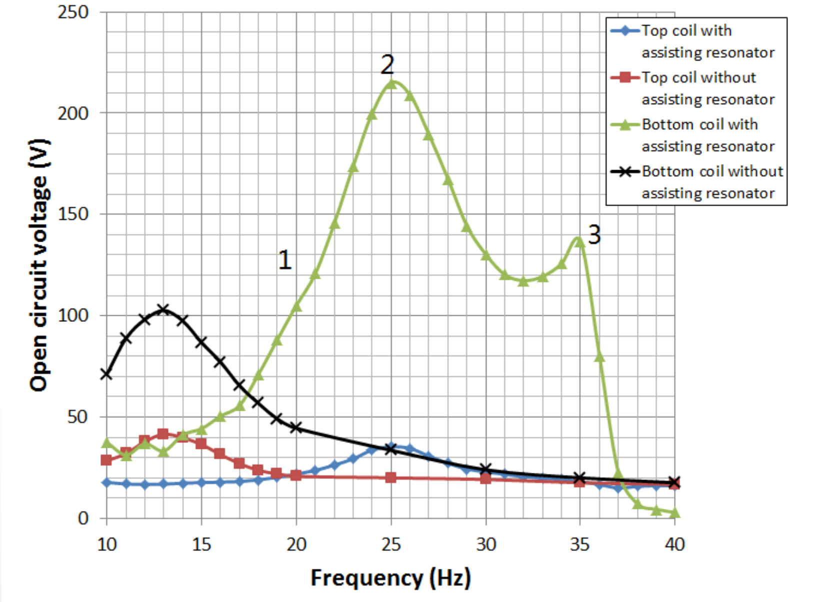
0.5 ***g*** ($4.9\ \mathrm{m{\cdot}s^{-2}}$) 0.6 ***g*** ($5.88\ \mathrm{m{\cdot}s^{-2}}$)

Peak 1: nonlinear (top and bottom magnets)
Peak 2: nonlinear (middle and top/bottom magnets)
Peak 3: linear* (coil spring)

Results



0.7 ***g*** (6.86 m·s^{-2})

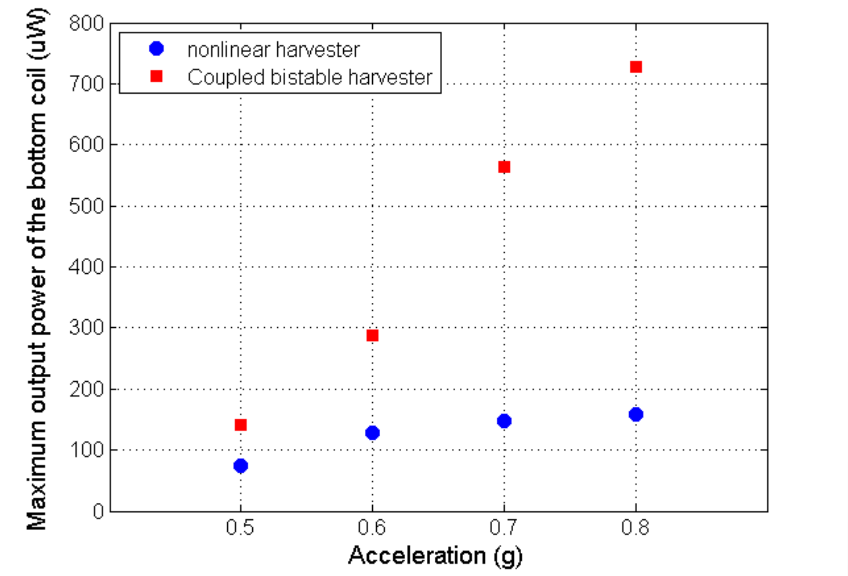


0.8 ***g*** (7.84 m·s^{-2})

Peak 1: nonlinear (top and bottom magnets)
Peak 2: nonlinear (middle and top/bottom magnets)
Peak 3: linear* (coil spring)

Results

- Power: Maximum output power is generated when connected to the optimal resistive load of 13 Ω.



- Half power bandwidth

Acceleration (*g*)	**0.5**	**0.6**	**0.7**	**0.8**
Bandwidth of the nonlinear harvester (Hz)	4	6.5	7	7.5
Bandwidth of coupled bistable harvester (Hz)	14.5	14	15	14

Conclusions

Conclusions

- Frequency tuning
  - Mechanical tuning methods have a larger tuning range.
  - Electrical tuning methods have a higher frequency resolution.
  - Electrical tuning methods consume less energy than mechanical tuning methods.
  - Applications of a tunable vibration energy harvester was demonstrated.
  - Performance of a linear harvester is compromised under wideband excitations.
- Coupled bistable structure
  - The coupled bistable structure requires lower excitation to trigger the bistable operation compared to conventional bistable structures.
  - Coupled bistable energy harvesters have better performance than both linear and Duffing's nonlinear energy harvesters under wideband excitations.

Acknowledgement

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  Steve Beeby, John Tudor, Alex Weddell, Ivo Ayala, Derek Arthur, Abiodun Komolafe

- Perpetuum Ltd,

  Steve Roberts, Thomas Mouille, Adam Wasenczuk

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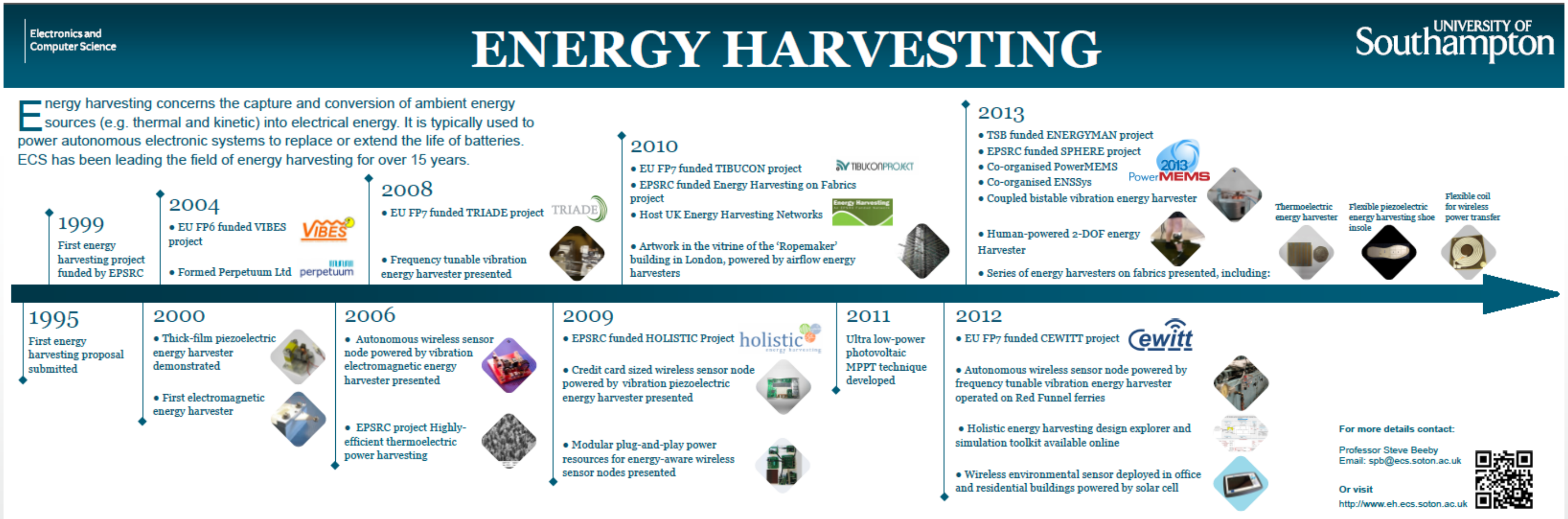
Thank you for your attention!

Questions?



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