

# Broadband Vibration Energy Harvesting

Frequency tuning and bistable solutions

Dr Dibin Zhu

Energy Harvesting 2015  
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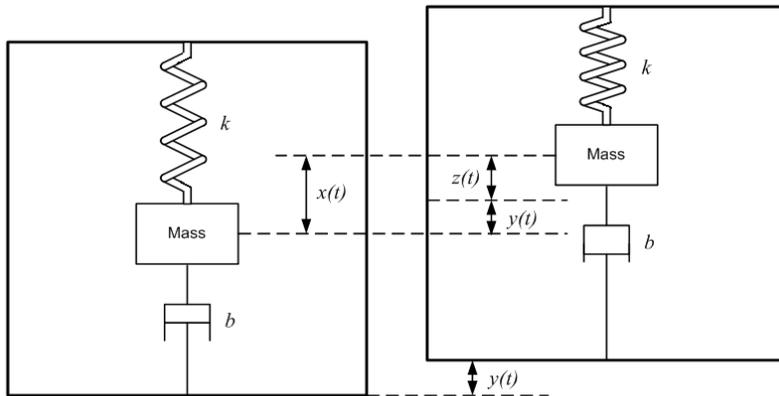
# Overview

- 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

# Motivation

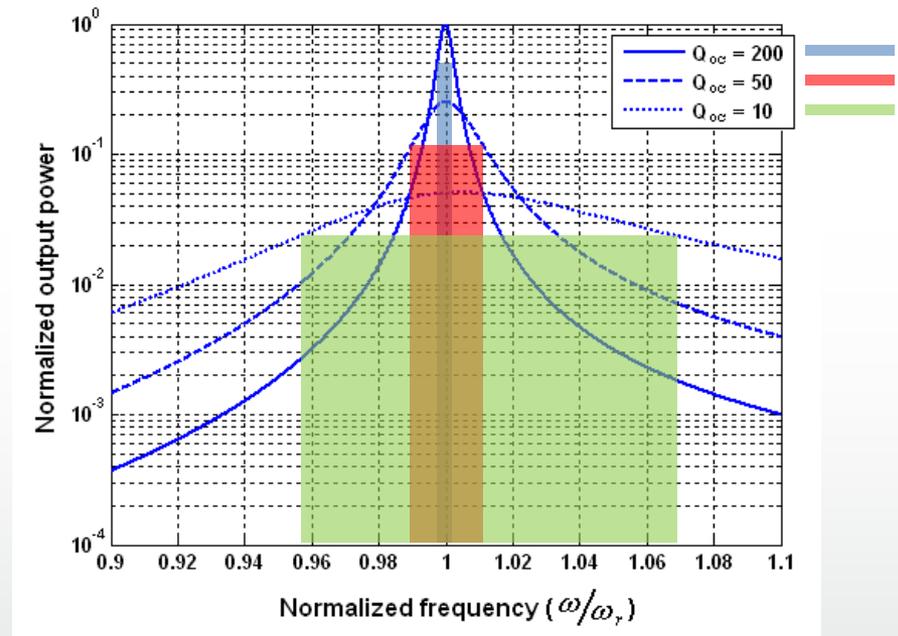
# Motivation

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

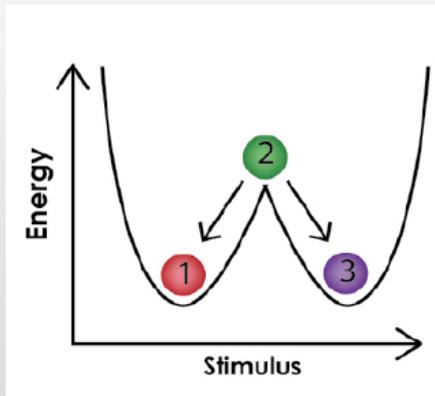
**Motivation:** to increase operational bandwidth of vibration energy harvesters:

- Resonant frequency tuning

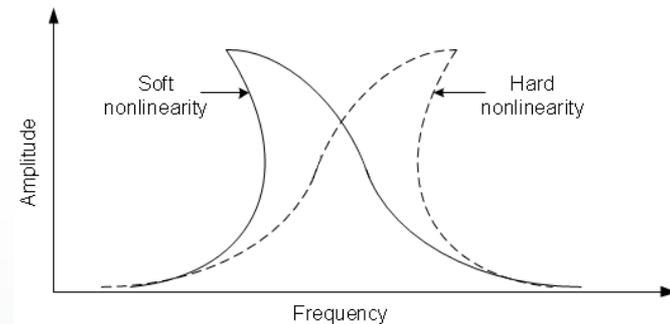
$$f_{\text{resonant}} = f_{\text{vibration}}$$

Mechanical/electrical methods

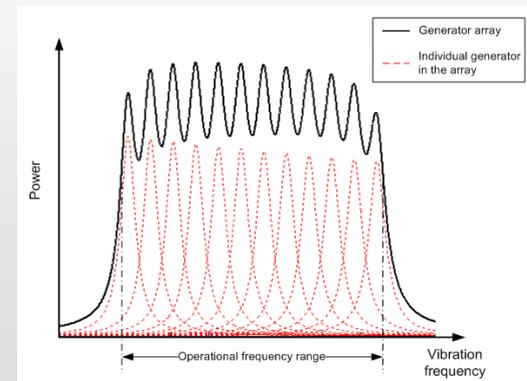
- Bistable structure



- Duffing's nonlinear structure



- Harvester array



# Frequency Tuning

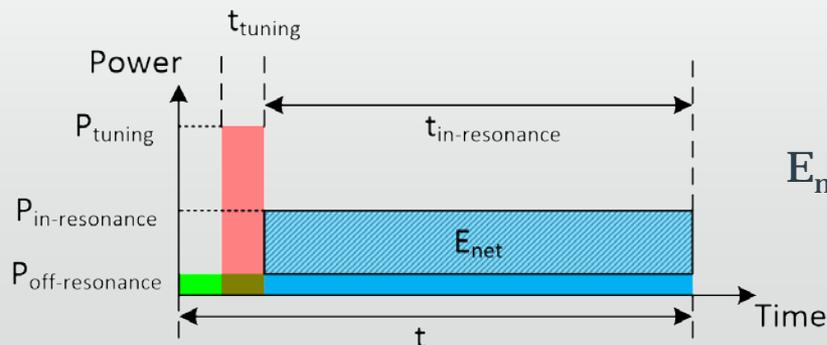
## Basics

# 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.



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

# 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.

# Frequency Tuning

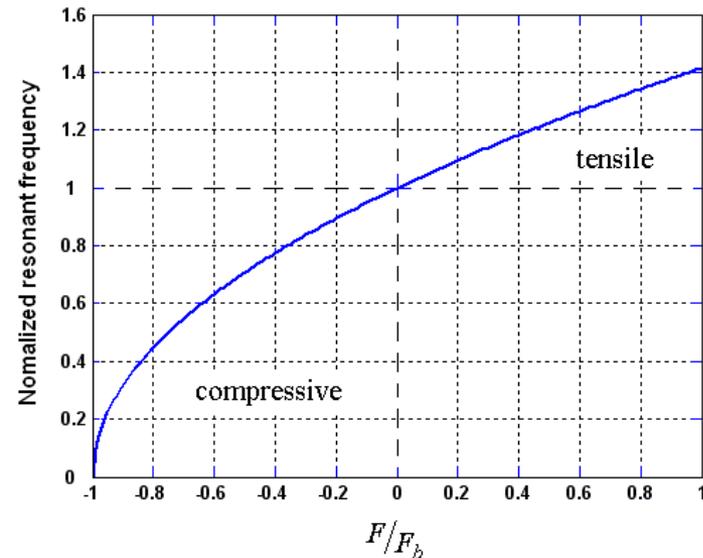
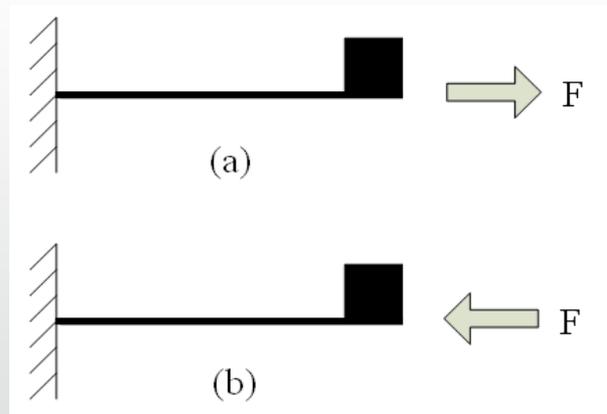
## Mechanical tuning method

# Principle

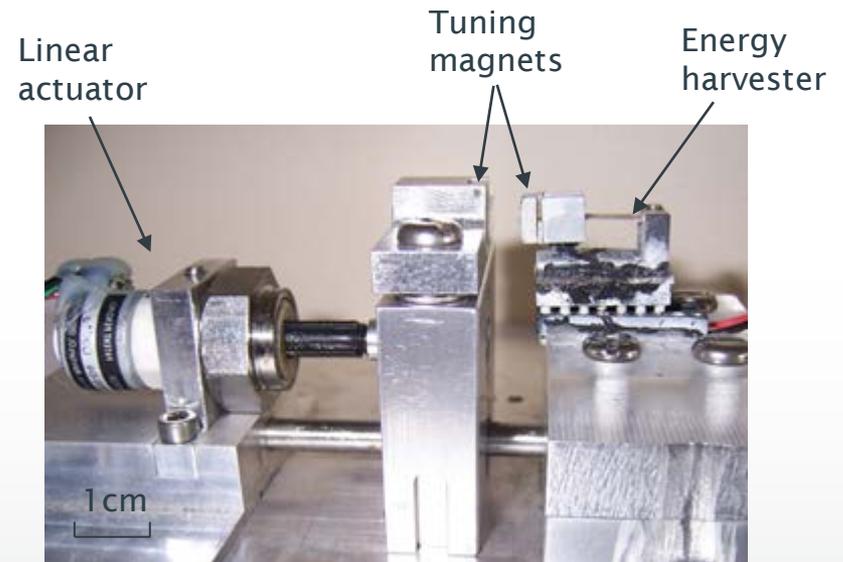
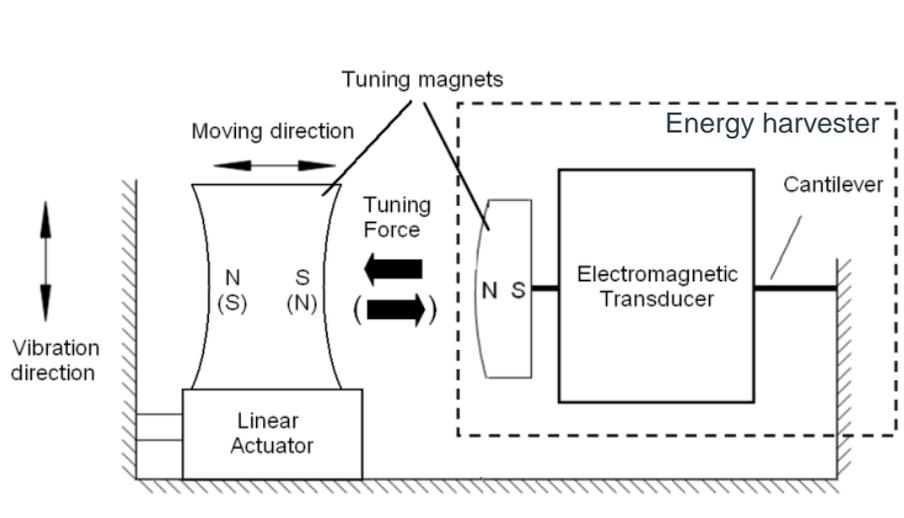
For a cantilever based energy harvester operating in the fundamental flexural mode (mode 1); its resonant frequency an axial load,  $f_{r1}'$ , is given by:

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

$F$ : axial load  
 $F_b$ : buckling force



# A Tunable Vibration Energy Harvester

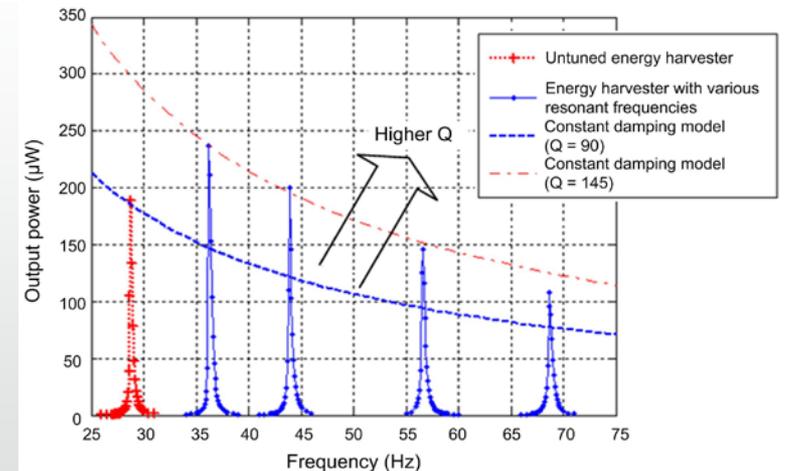
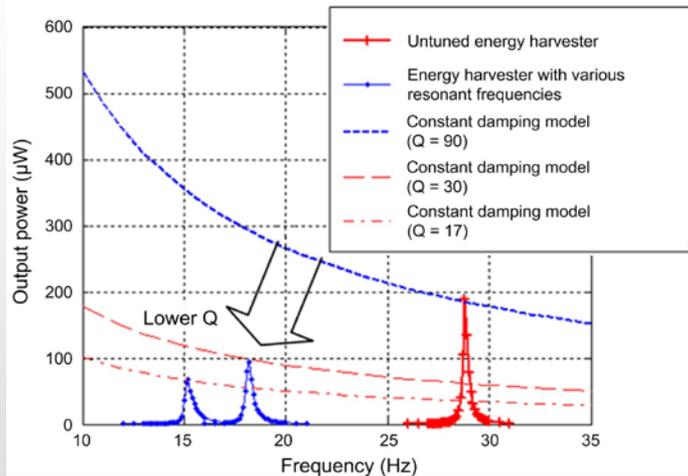
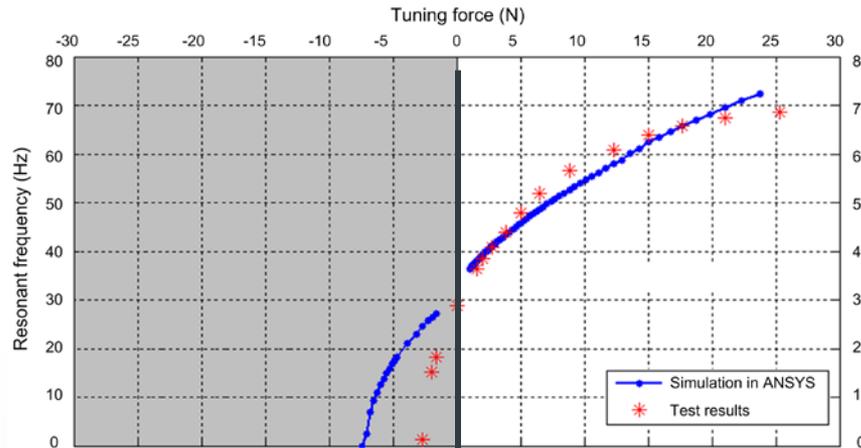


- Contactless (magnetic) force is applied.
- A linear actuator is used to adjust the position of the tuning magnet, thus the tuning force.

# Experimental Results

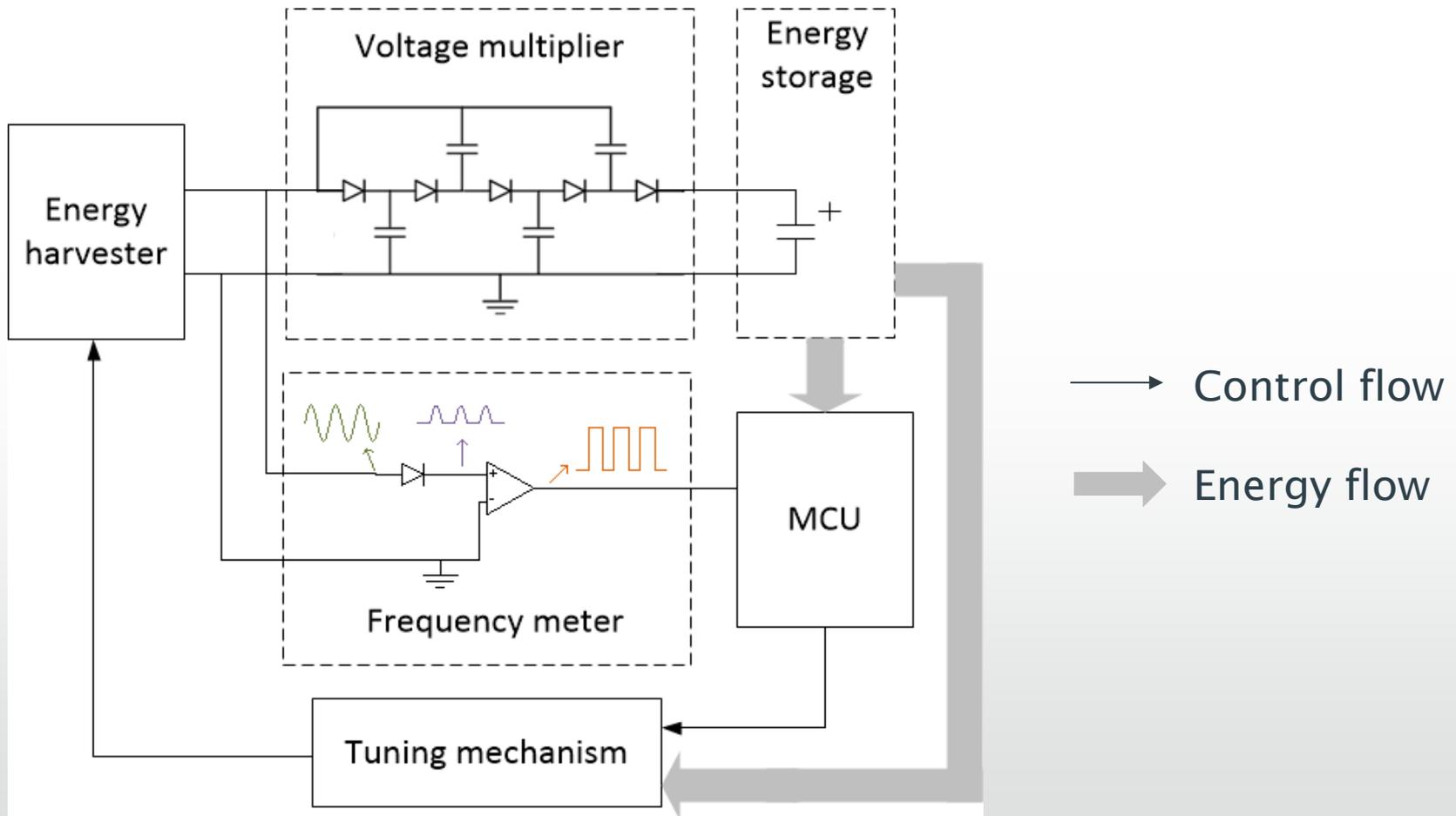
Compressive  
force

Tensile force

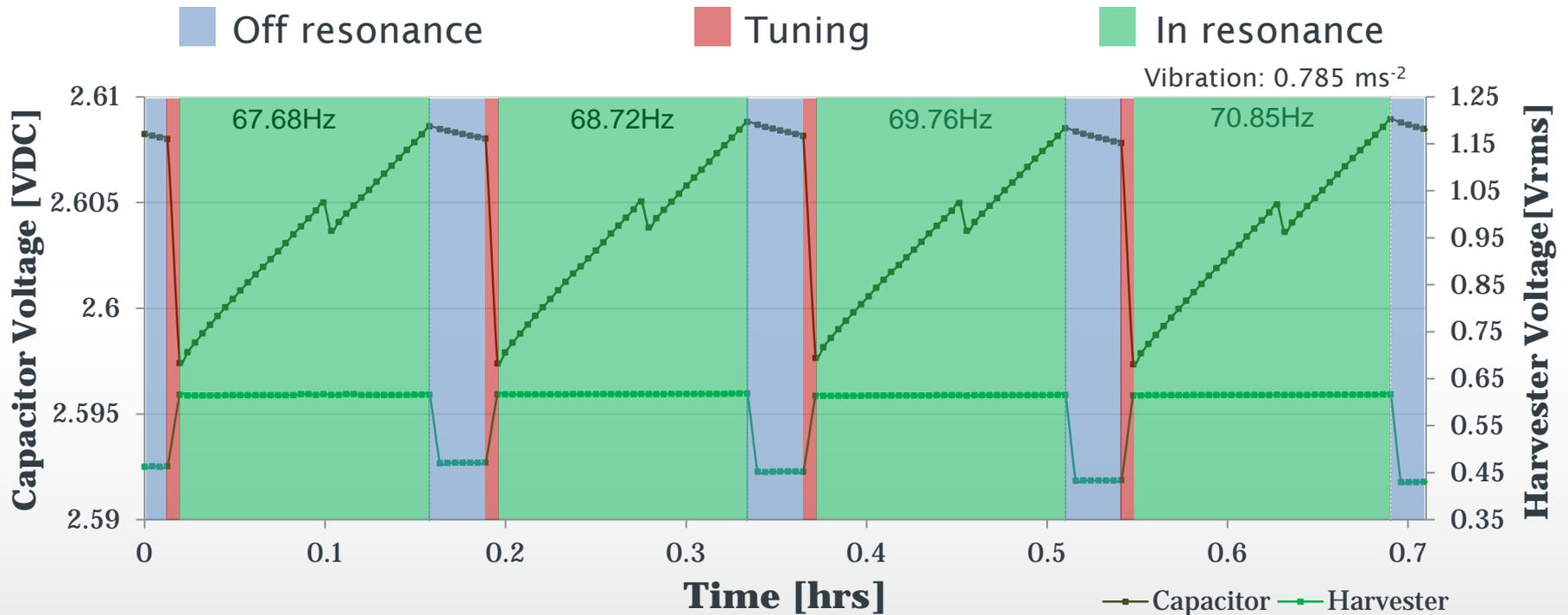


- Compressive forces increase damping while tensile forces reduce damping.

# Closed-loop Frequency Tuning



# Closed-loop Frequency Tuning



- Frequency shifts  $\sim 1\text{Hz}$
- Harvester's voltage drops when off-resonance
- MCU wakes from sleep every 320 seconds

# Case Study

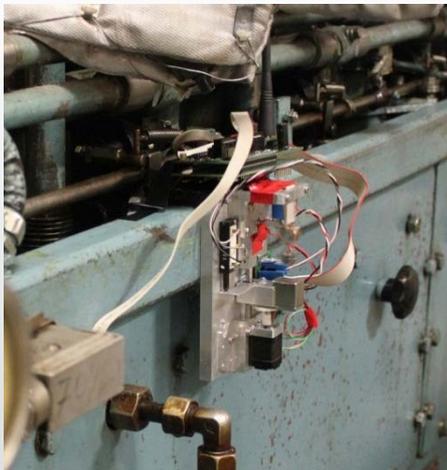


A Red Funnel ferry running between Southampton and Isle of Wight

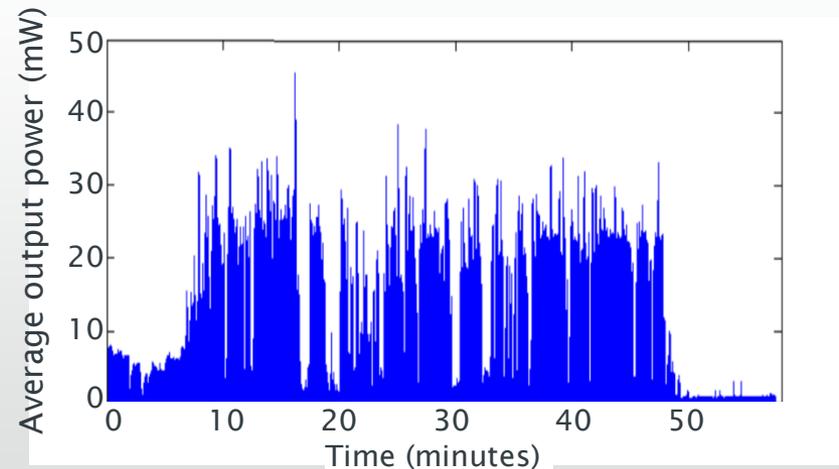
## Typical vibration on the engine

Normal speed (~715RPM)		Fast speed (~750RPM)	
$f$ (Hz)	Ampl. ( $mg_{pk}$ )	$f$ (Hz)	Ampl. ( $mg_{pk}$ )
47-48 Hz	700 - 950	~50	450

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

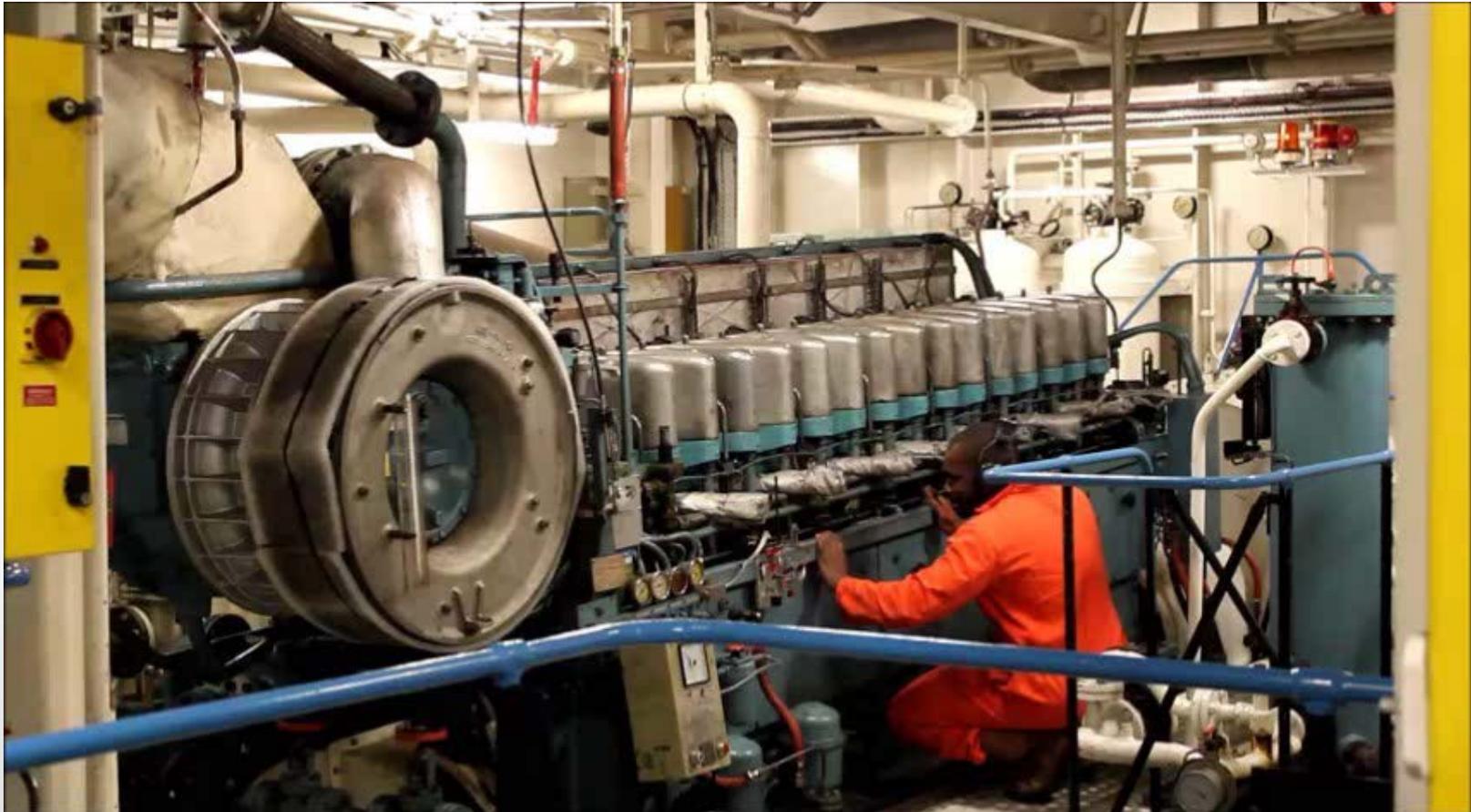


A tunable vibration energy harvester powering wireless sensors on a Red Funnel ferry



Real-time output power of the harvester during one crossing

# Case Study

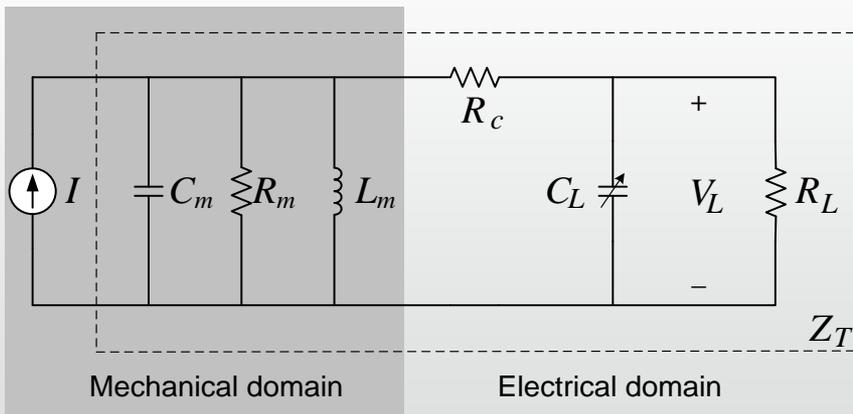
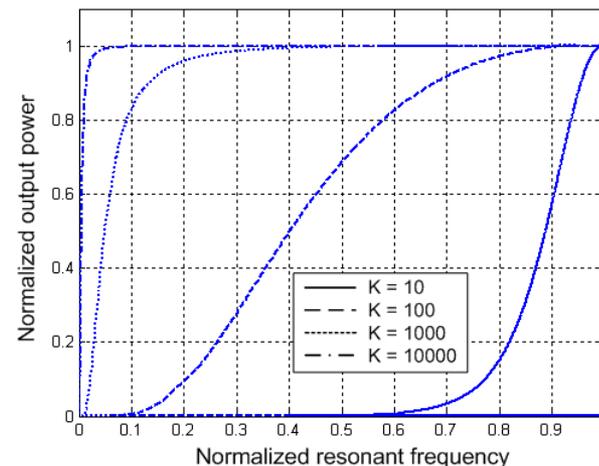
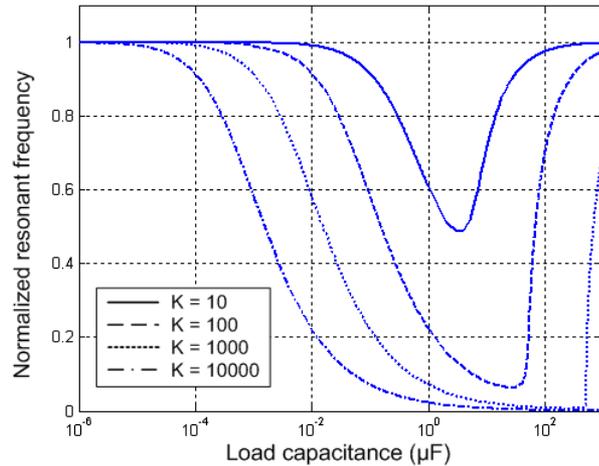


# Frequency Tuning

## Electrical tuning method

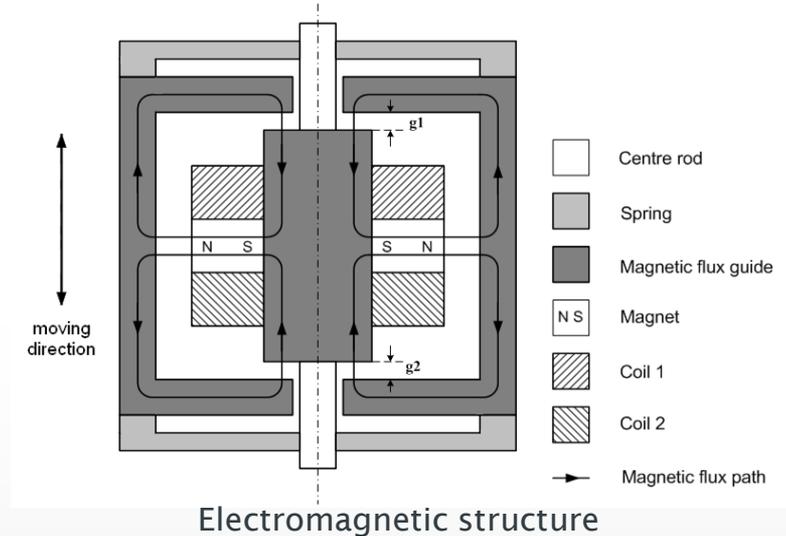
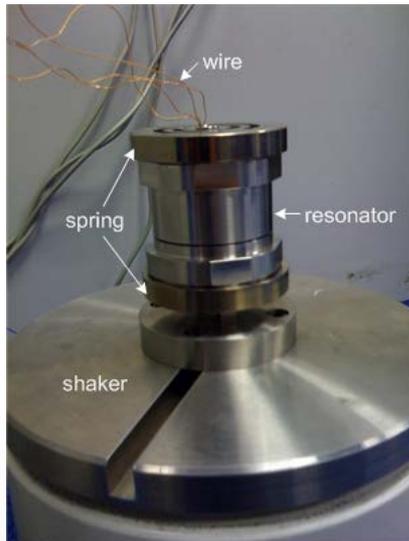
# Principle

- 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.

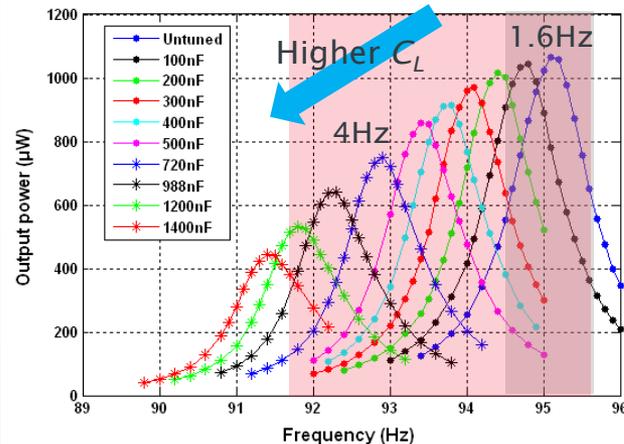


Equivalent circuit of an electrically tunable vibration energy harvester

# An Electrically Tunable Vibration Energy Harvester



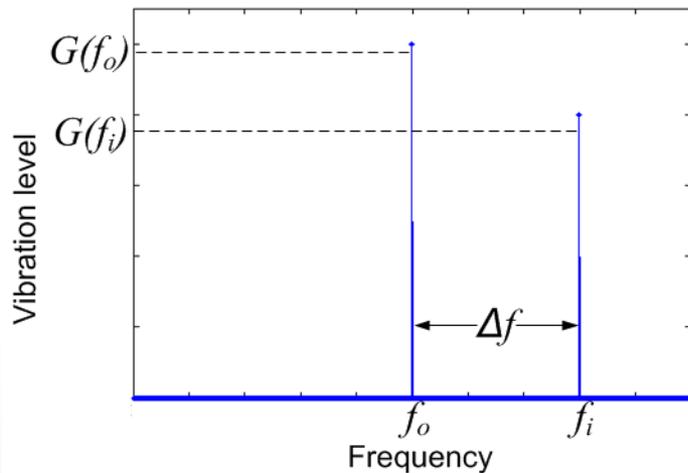
Excitation level:  
10mG



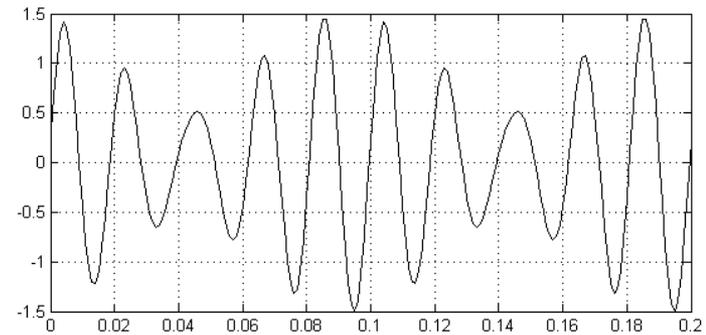
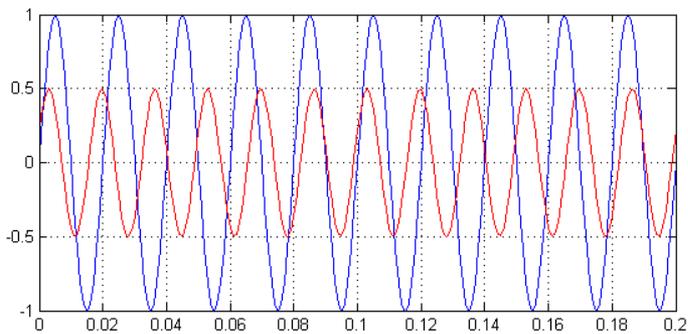
# Frequency Tuning

Performance of linear energy harvesters  
under multiple-peak excitations

# Multiple-peak Excitations



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



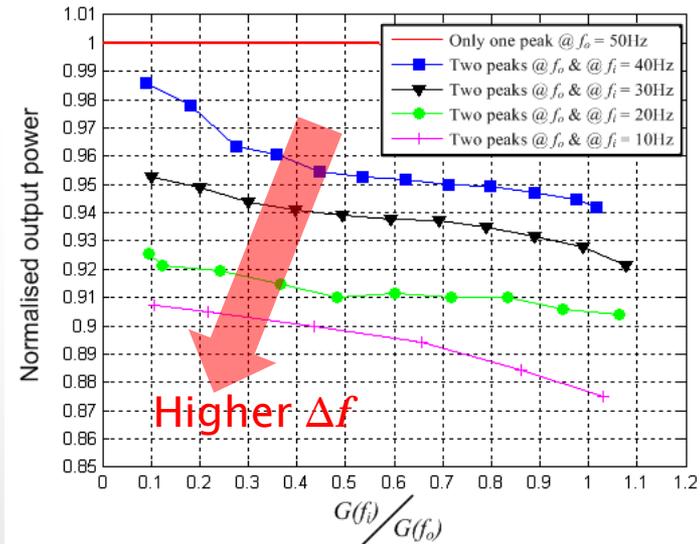
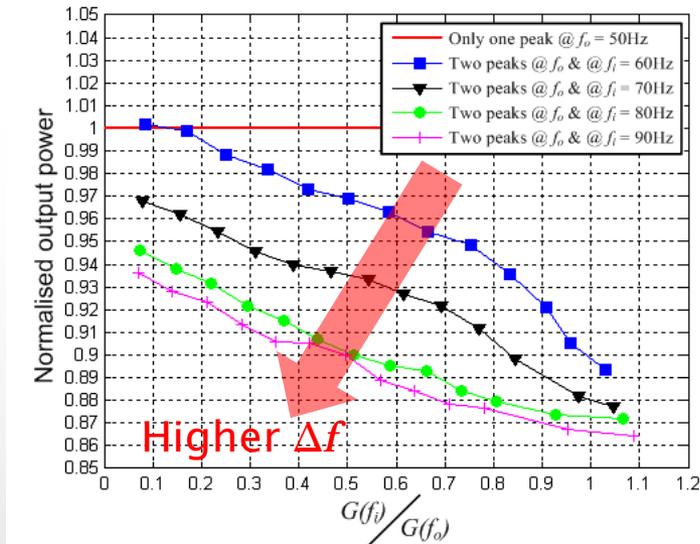
— Main signal  
— Interference signal

— Combined signal

# Performance of Linear Energy Harvesters under Multiple-peak Excitations

$$f_i > f_o$$

$$f_i < f_o$$

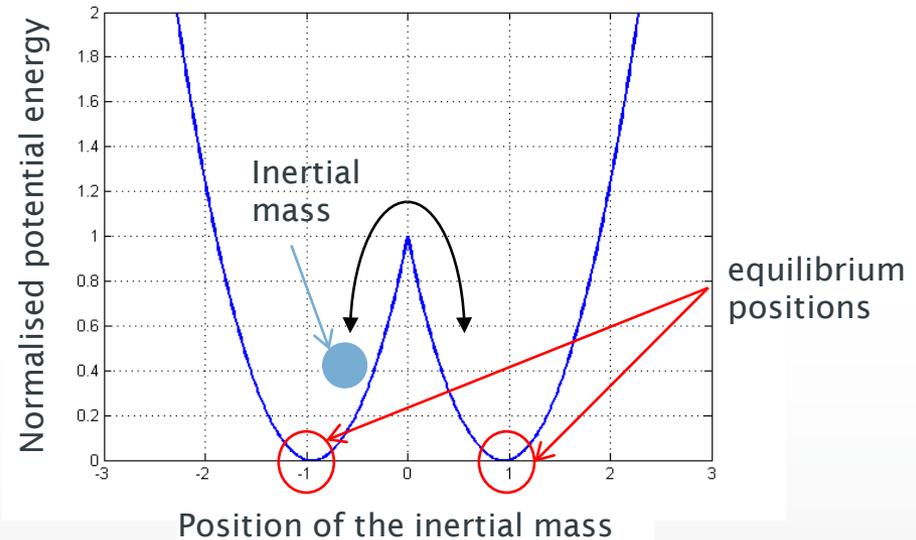
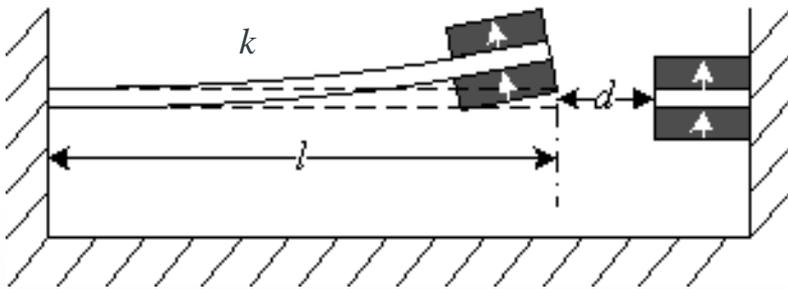


Output power drops as

- Frequency difference increases
- Amplitude of the interference peak increases

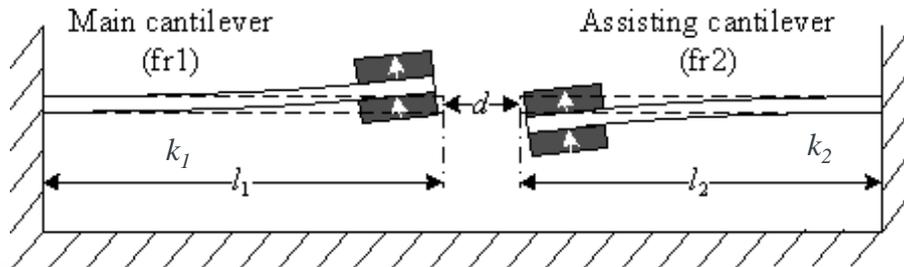
# Coupled Bistable Structures for Energy Harvesting Applications

# Conventional Bistable Structures

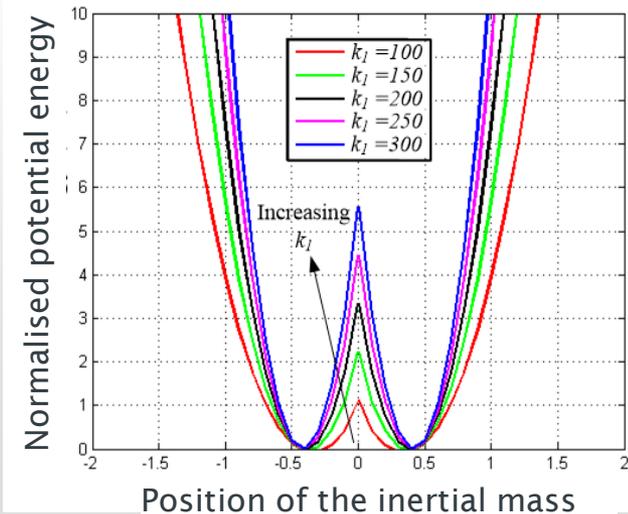
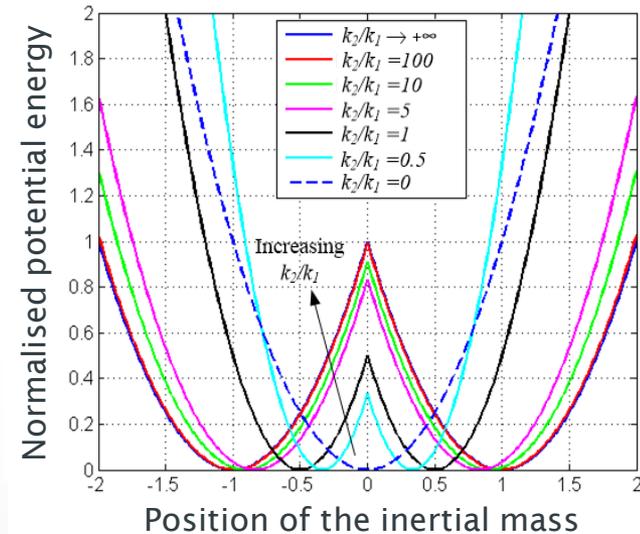


- It consists of a cantilever with a magnet at the tip and a fixed magnet.
- Repelling force between the two magnets.
- Inertial mass jumps between two equilibrium positions.
- Bistable vibration energy harvesters have better performance under wideband excitation compared to a linear harvester.
- It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

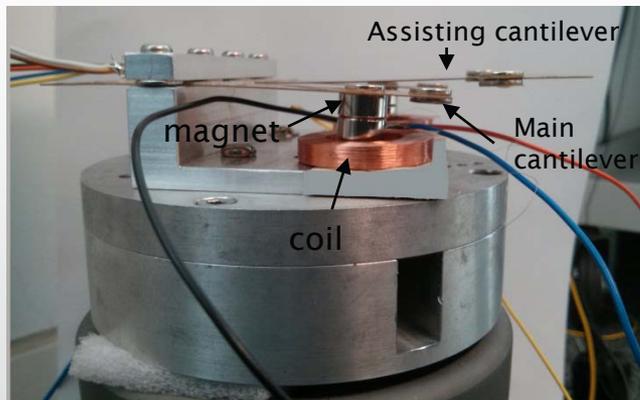
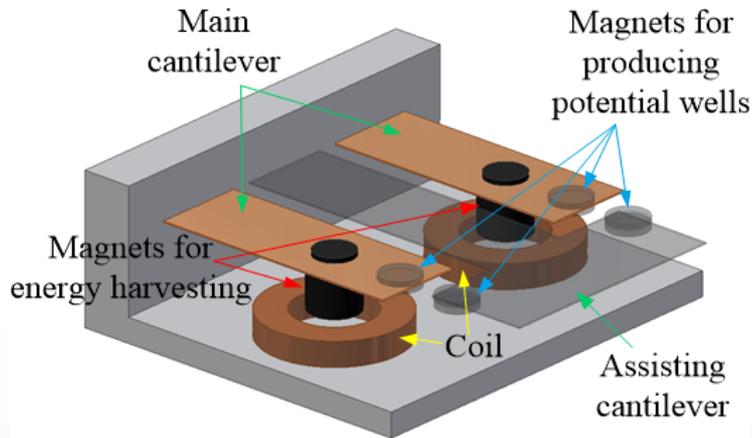
# Coupled Bistable Structures



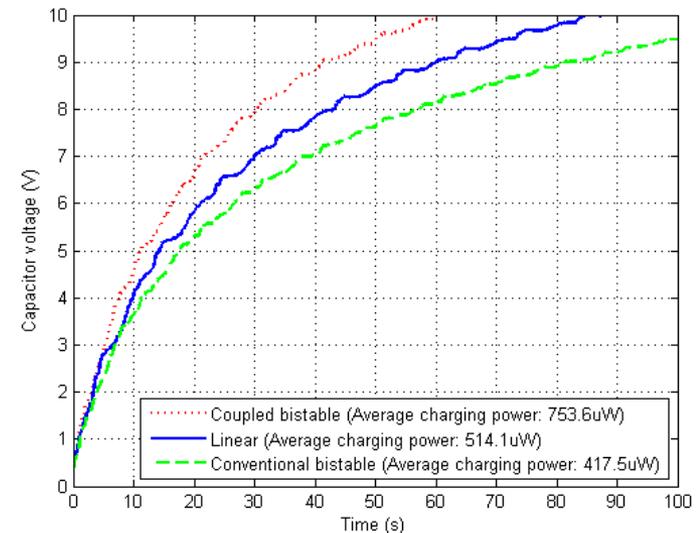
- The coupled bistable structure requires lower excitation to trigger the bistable operation.
- It is preferred that the resonant frequency of the assisting cantilever is lower than that of the main cantilever ( $k_2 < k_1$ ).



# Coupled Bistable Energy Harvester 1



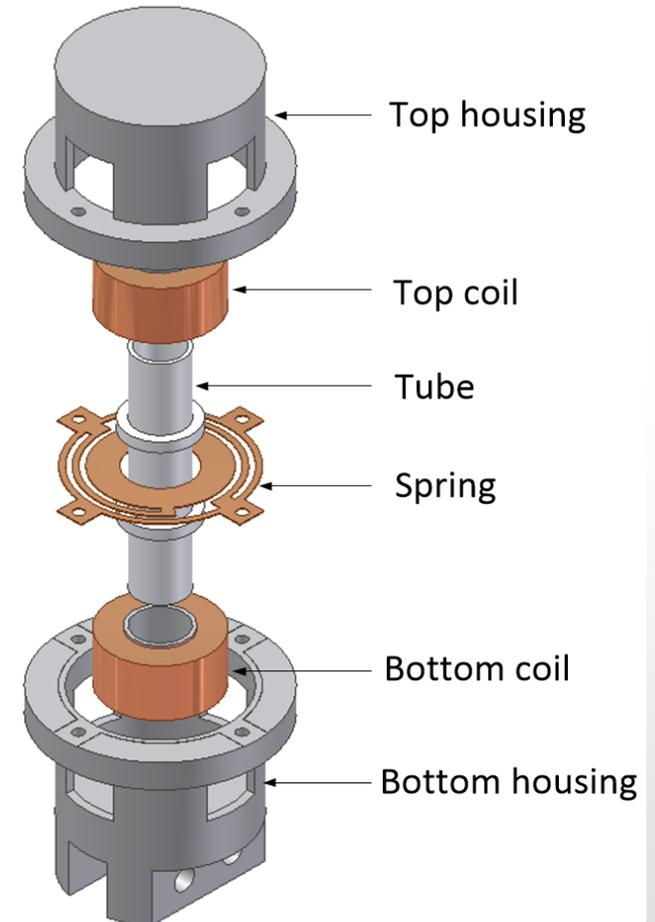
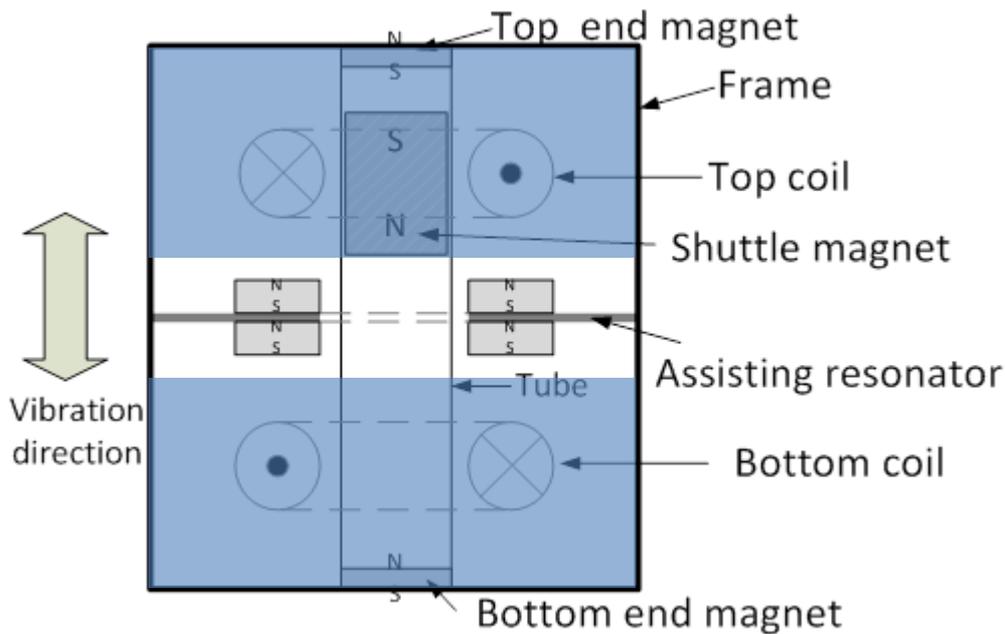
- Main cantilevers: 28.9 Hz
- Assisting cantilever: 16 Hz



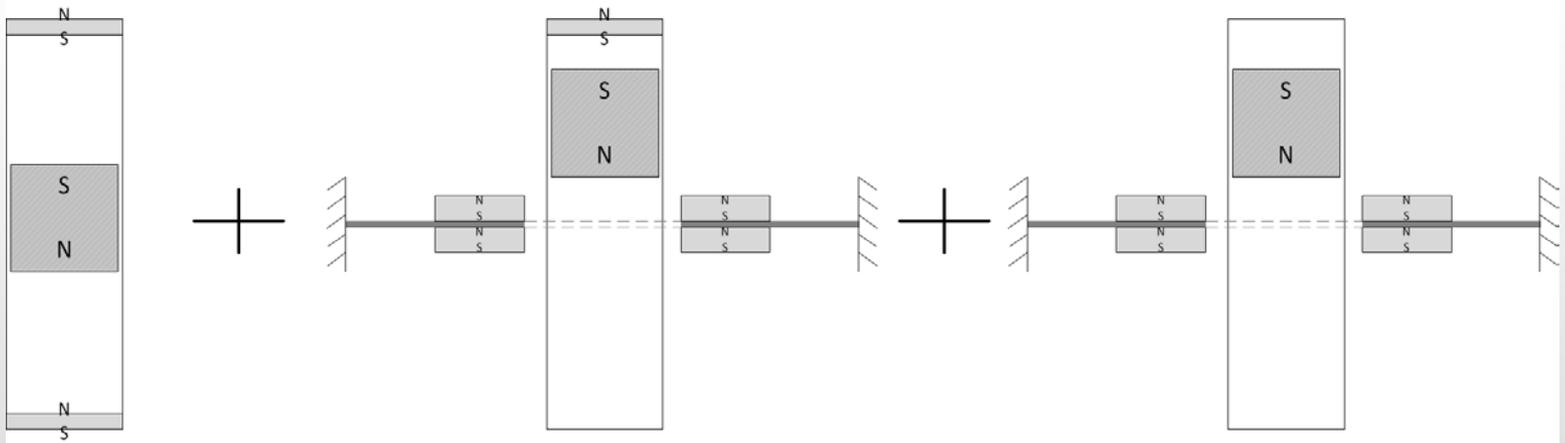
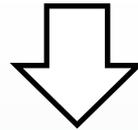
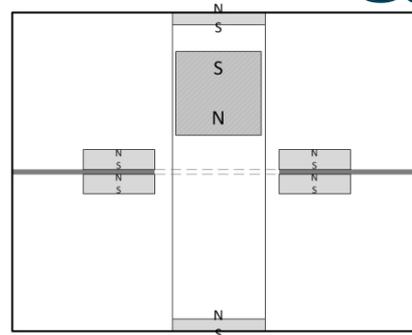
Electromagnetic energy harvester with a couple bistable structure

Comparison of charging rate under white noise excitation

# Coupled Bistable Energy Harvester 2



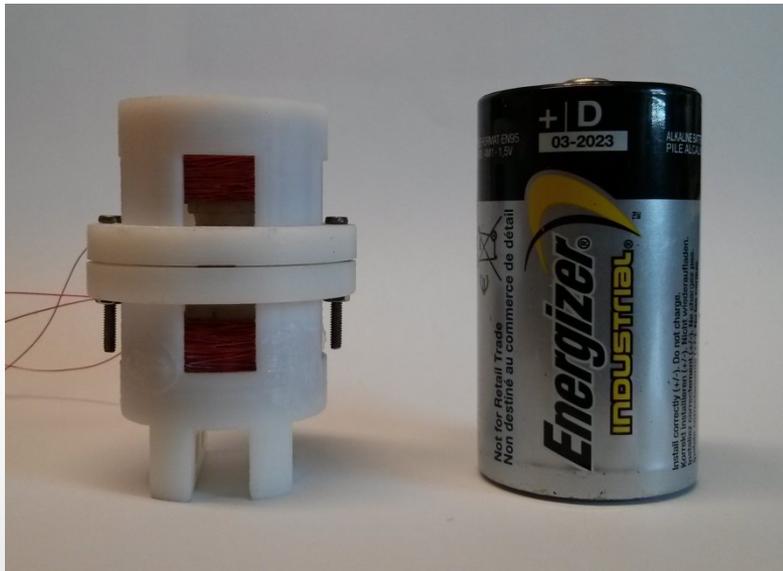
# Coupled Bistable Energy Harvester 2



Nonlinear structure (top and bottom magnets) + Nonlinear structure (middle and bottom/top magnets)

Linear resonator\* (coil spring)

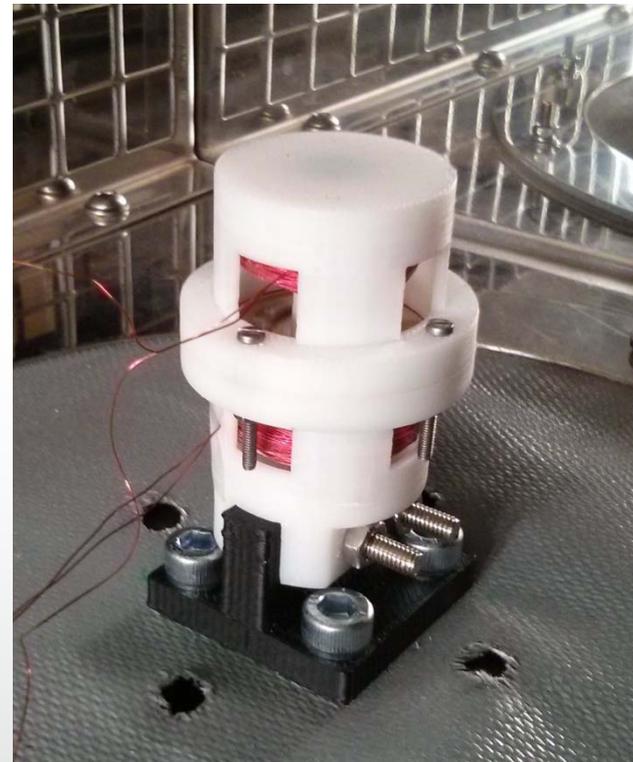
# Assembled Harvester



Harvester

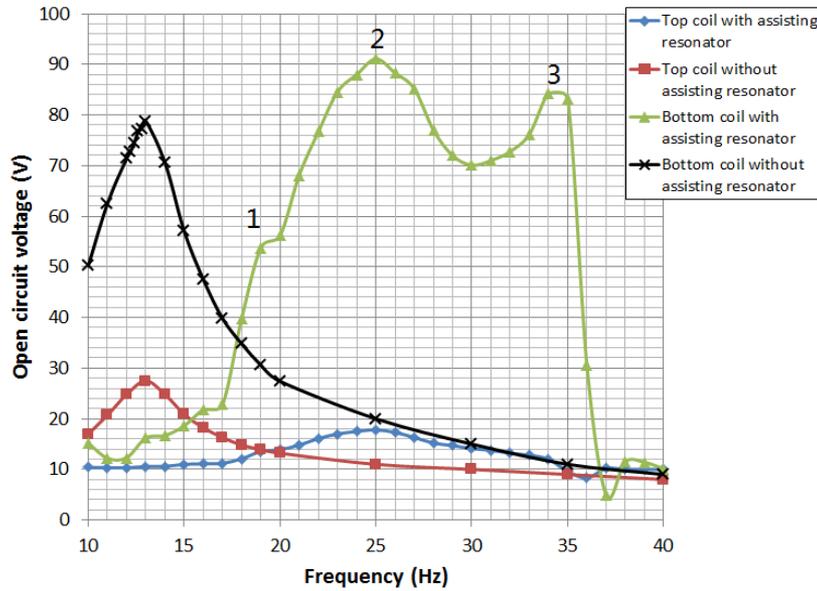
D-battery

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

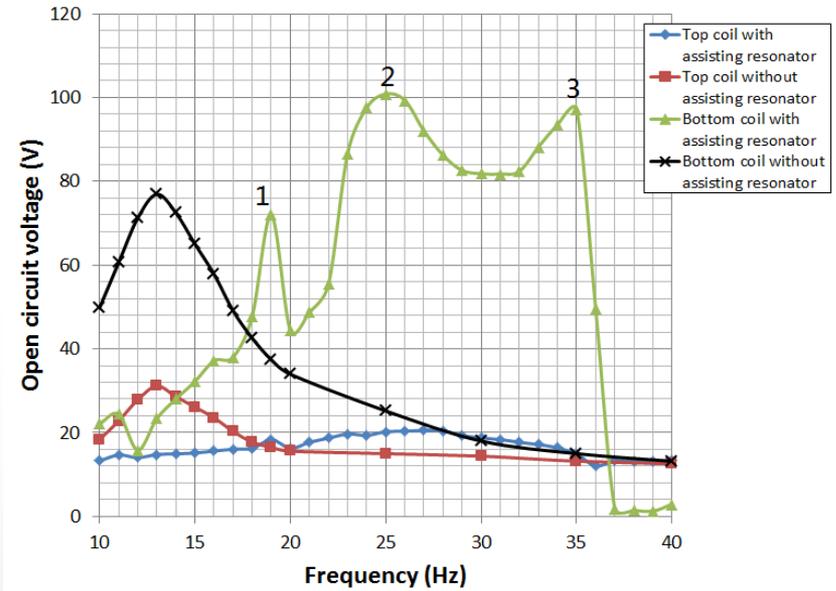


Harvester mounted on the  
shaker

# Results



0.5  $g$  (4.9  $m \cdot s^{-2}$ )



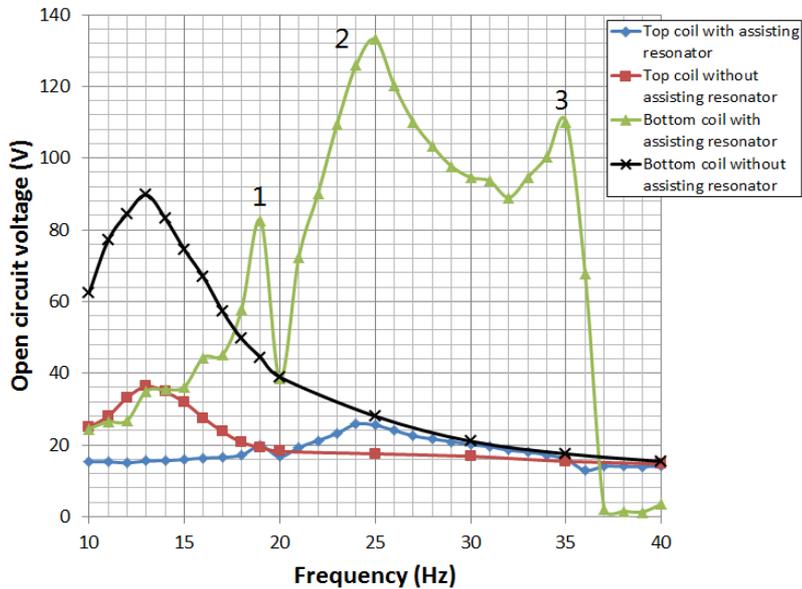
0.6  $g$  (5.88  $m \cdot s^{-2}$ )

Peak 1: nonlinear (top and bottom magnets)

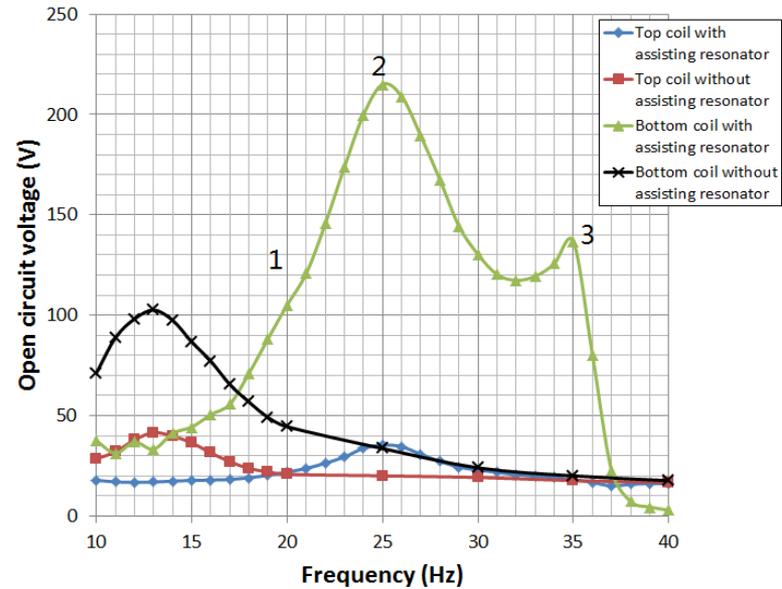
Peak 2: nonlinear (middle and top/bottom magnets)

Peak 3: linear\* (coil spring)

# Results



$0.7 \text{ g}$  ( $6.86 \text{ m}\cdot\text{s}^{-2}$ )



$0.8 \text{ g}$  ( $7.84 \text{ m}\cdot\text{s}^{-2}$ )

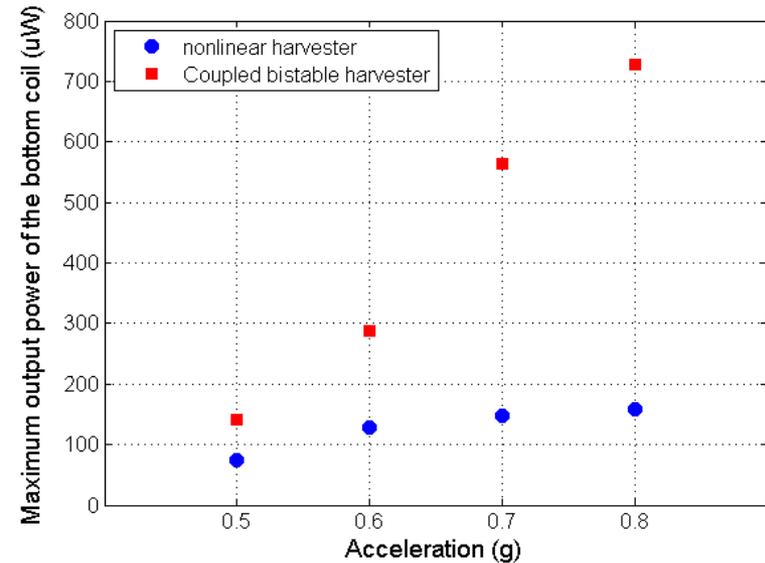
Peak 1: nonlinear (top and bottom magnets)

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  $13 \Omega$ .
- **Half power bandwidth**



<b>Acceleration (g)</b>	<b>0.5</b>	<b>0.6</b>	<b>0.7</b>	<b>0.8</b>
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

- **University of Southampton**

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- **Perpetuum Ltd,**

Steve Roberts, Thomas Mouille, Adam Wasenczuk

# Thank you for your attention!

## Questions?

Electronics and Computer Science
UNIVERSITY OF Southampton

## ENERGY HARVESTING

**E**nergy harvesting concerns the capture and conversion of ambient energy sources (e.g. thermal and kinetic) into electrical energy. It is typically used to power autonomous electronic systems to replace or extend the life of batteries. ECS has been leading the field of energy harvesting for over 15 years.

<p><b>1995</b> First energy harvesting proposal submitted</p>	<p><b>1999</b> First energy harvesting project funded by EPSRC</p>	<p><b>2000</b> • Thick-film piezoelectric energy harvester demonstrated • First electromagnetic energy harvester</p>	<p><b>2004</b> • EU FP6 funded VIBES project • Formed Perpetuum Ltd</p>	<p><b>2006</b> • Autonomous wireless sensor node powered by vibration electromagnetic energy harvester presented • EPSRC project Highly-efficient thermoelectric power harvesting</p>	<p><b>2008</b> • EU FP7 funded TRIADE project • Frequency tunable vibration energy harvester presented</p>	<p><b>2009</b> • EPSRC funded HOLISTIC Project • Credit card sized wireless sensor node powered by vibration piezoelectric energy harvester presented • Modular plug-and-play power resources for energy-aware wireless sensor nodes presented</p>	<p><b>2010</b> • EU FP7 funded TIBUCON project • EPSRC funded Energy Harvesting on Fabrics project • Host UK Energy Harvesting Networks • Artwork in the vitrine of the 'Ropemaker' building in London, powered by airflow energy harvesters</p>	<p><b>2011</b> Ultra low-power photovoltaic MPPT technique developed</p>	<p><b>2012</b> • EU FP7 funded CEWITT project • Autonomous wireless sensor node powered by frequency tunable vibration energy harvester operated on Red Funnel ferries • Holistic energy harvesting design explorer and simulation toolkit available online • Wireless environmental sensor deployed in office and residential buildings powered by solar cell</p>	<p><b>2013</b> • TSB funded ENERGYMAN project • EPSRC funded SPHERE project • Co-organised PowerMEMS • Co-organised ENSYSys • Coupled bistable vibration energy harvester • Human-powered 2-DOF energy Harvester • Series of energy harvesters on fabrics presented, including:</p>
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For more details contact:  
Professor Steve Beeby  
Email: [spb@ecs.soton.ac.uk](mailto:spb@ecs.soton.ac.uk)  
Or visit  
<http://www.eh.ecs.soton.ac.uk>



<http://www.eh.ecs.soton.ac.uk>

Dr Dibin Zhu  
dz@ecs.soton.ac.uk