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WIDEBAND ENERGY HARVESTING

(ICT-ENERGY SUMMER SCHOOL 2016)

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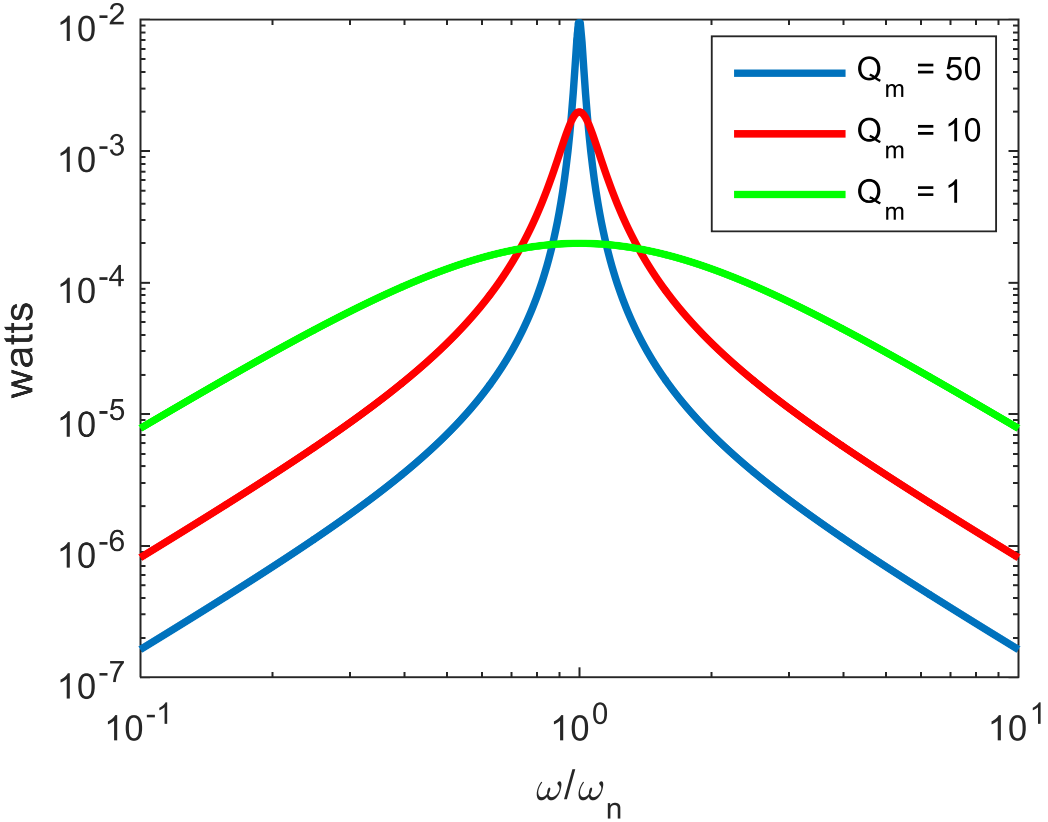
Outline for Short Course

- Introduction and Linear Energy Harvesting
- Energy Harvesting Transducers
  - Electromagnetic
  - Piezoelectric
  - Electrostatic
- **Wideband and Nonlinear Energy Harvesting**
- Applications

Remember This from Earlier?



A = 1 m/s^2
m = 1 kg
$\omega_n = 2\pi 100$ rad/s

Power at resonance is highly dependent on Q.

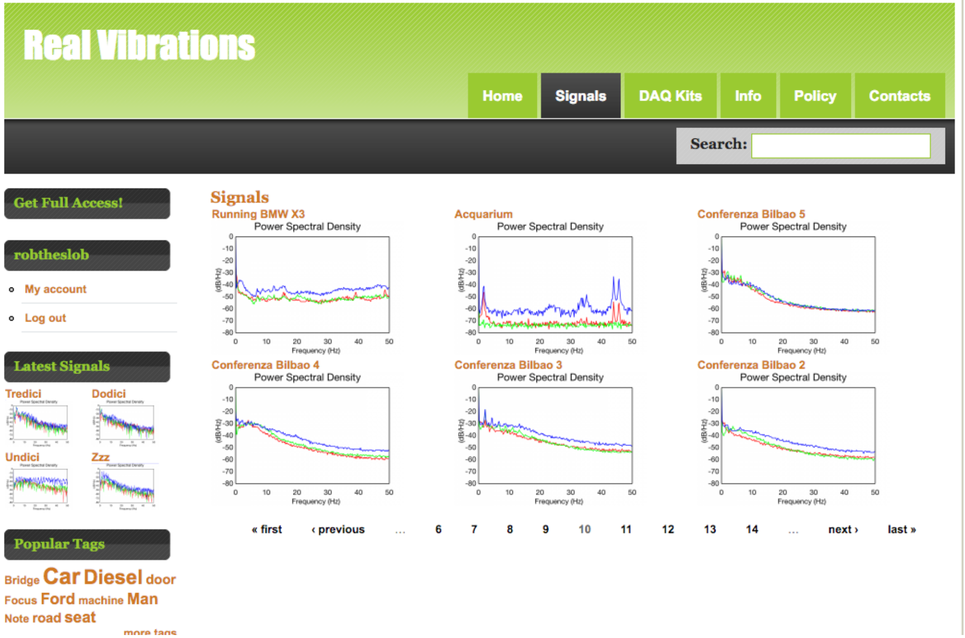
At high Q, where power is good, half-power bandwidth is extremely narrow, which is one of the big problems with vibration energy harvesters.

Is Narrow-bandwidth a Problem?

- Not always
  - Machine vibrations are often at stable frequencies of either 50 Hz or 60 Hz driven by AC motors
  - Some structures will have some strong dominant frequencies based on the structure's own natural frequency
  - But, most vibration sources are either wideband or have a single dominant frequency that changes in time

Study Characterizing Vibration Sources *

- Vibration signals were acquired from the Noise in Physical Systems (NiPS) Real Vibrations database**
- Comprised of hundreds of signals from many sources – more than any other freely available database, to our knowledge



* R. Rantz and S. Roundy, SPIE Smart Structures and Materials+ Nondestructive Evaluation and Health Monitoring. 2016

** Neri, I., Travasso, F., Mincigrucci, R., Vocca, H., Orfei, F.., Gammaitoni, L., J. Intell. Mater. Syst. Struct. 23(18), 2095–2101 (2012).

Methodology

- Vibration signals were acquired from the Noise in Physical Systems (NiPS) Real Vibrations database
  - As of January 2016
- Signals that were determined to be of acceptable quality were used for the study
- A total of 333 signals were used in the classification procedure

Methodology

- In order to make dominant signals more apparent, a filtering technique was employed based on linear VEH theory
- According to the Velocity Damped Resonant Generator (VDRG) model, the upper bound on average power output of a linear VEH subject to harmonic excitation is

$$P_{avg} = \frac{\boldsymbol{A^2} m \zeta_e r^3}{\boldsymbol{\omega}\left((1-r^2)^2 + \left(2r(\zeta_m+\zeta_e)\right)^2\right)} \quad *$$

- Notice that power is proportional to A^2/ω

* Mitcheson et al., 2004

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Methodology

- Dominant signals were made more apparent by filtering by A^2/ω
  - In each FFT frame, frequency content below half of the maximum A^2/ω is filtered
- Both filtered and unfiltered spectrograms were generated for each signal in the study
- Spectrograms were examined individually and classified

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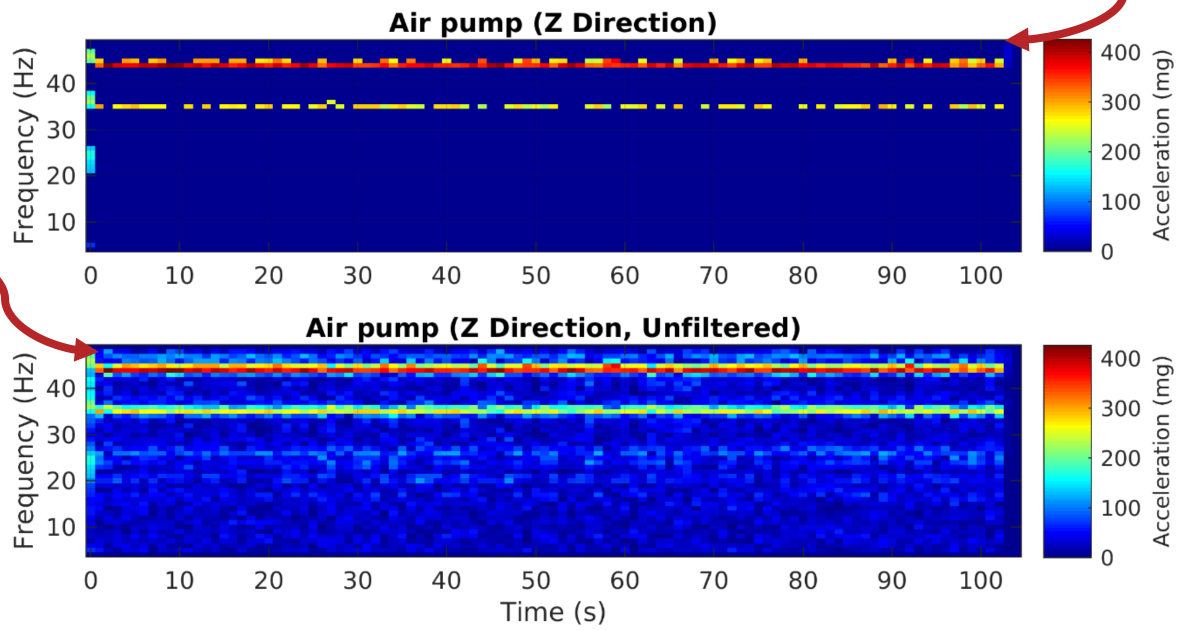
Methodology

- Classifications deemed important to VEH design:
  - Source of the vibration (animal, machine, vehicle, structure, unknown)
  - Number of "dominant" frequencies
    - If none, white or filtered noise
  - Nature of the dominant frequencies
    - Stationary frequencies
    - Nonstationary frequencies

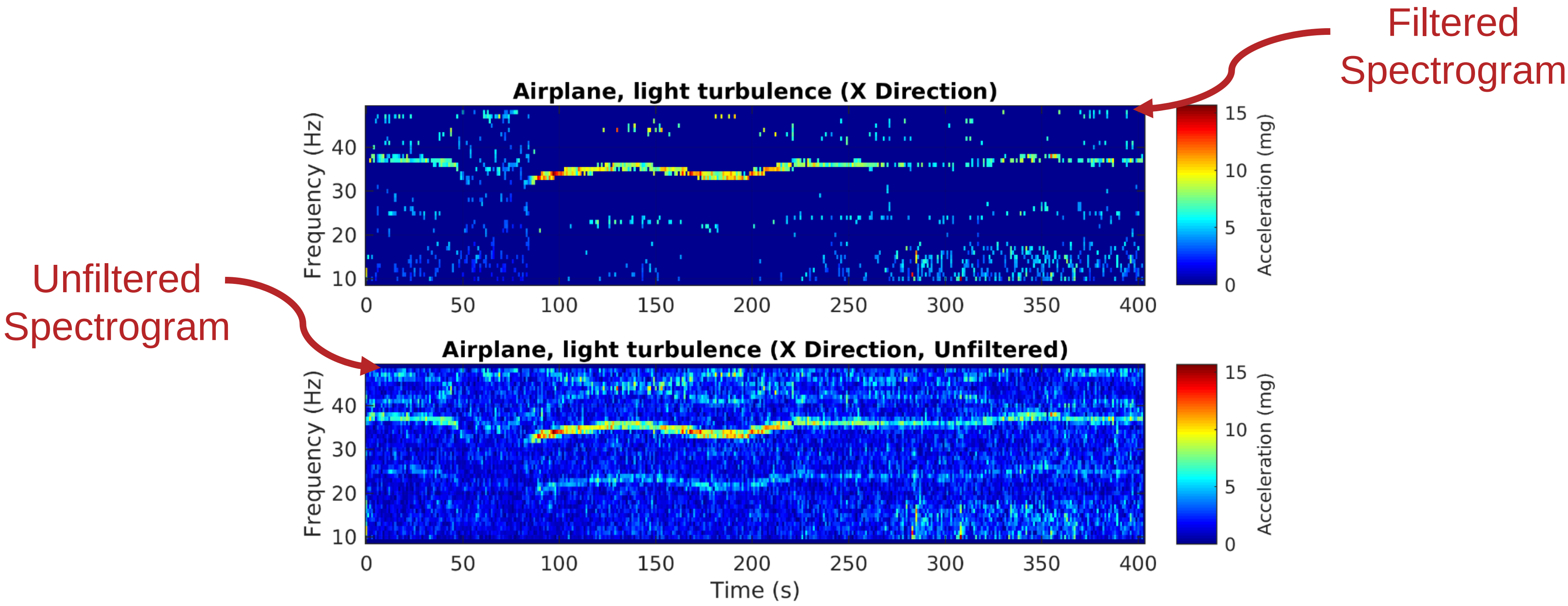
Methodology

- Example: two dominant, stationary frequencies



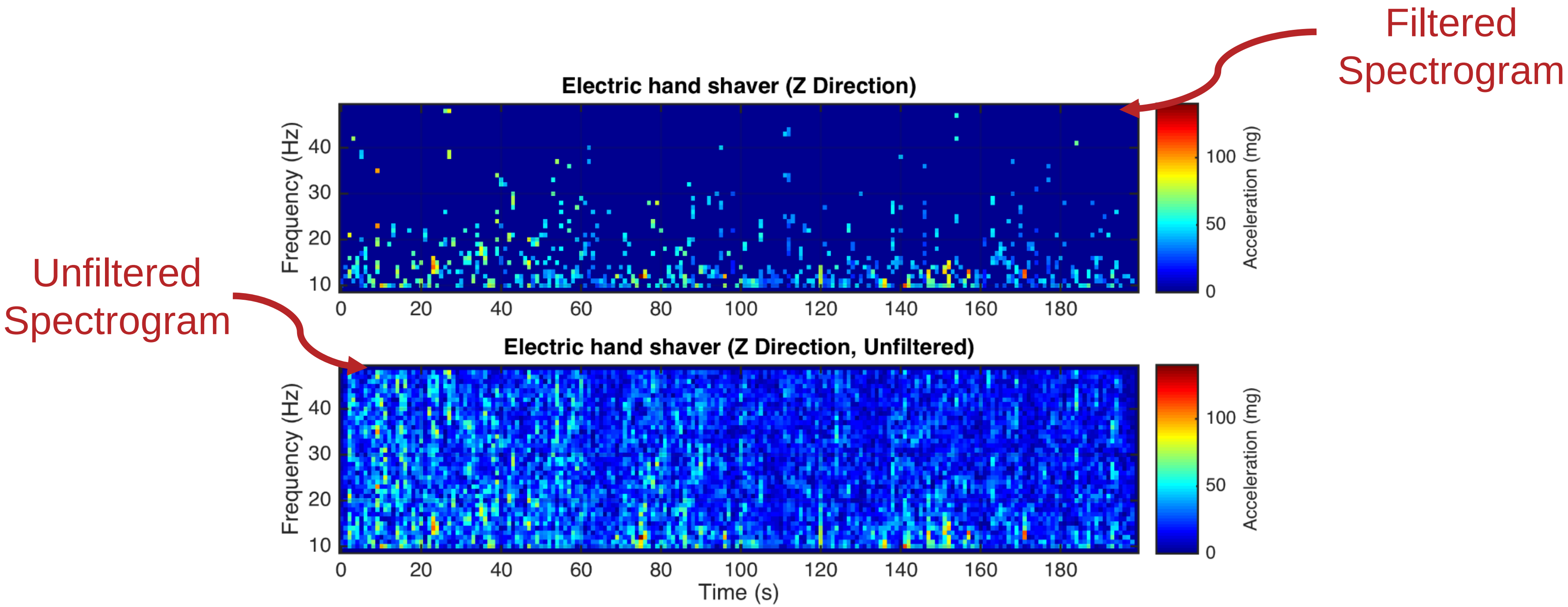
Methodology

- Example: one dominant, nonstationary frequency



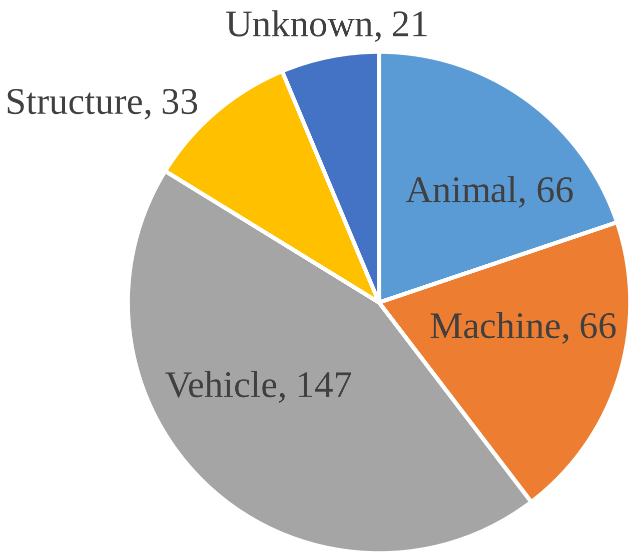
Methodology

- Example: "white noise" classification

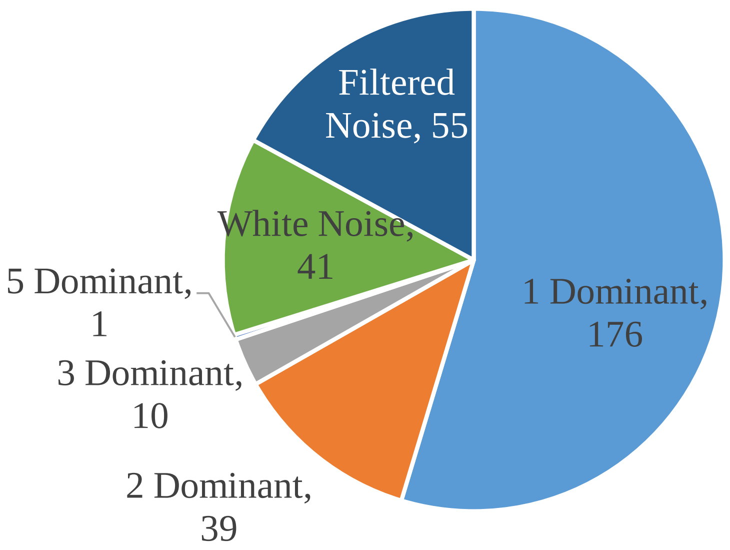


Results

All Signals by Source Classification



All Signals by Spectrogram Classification



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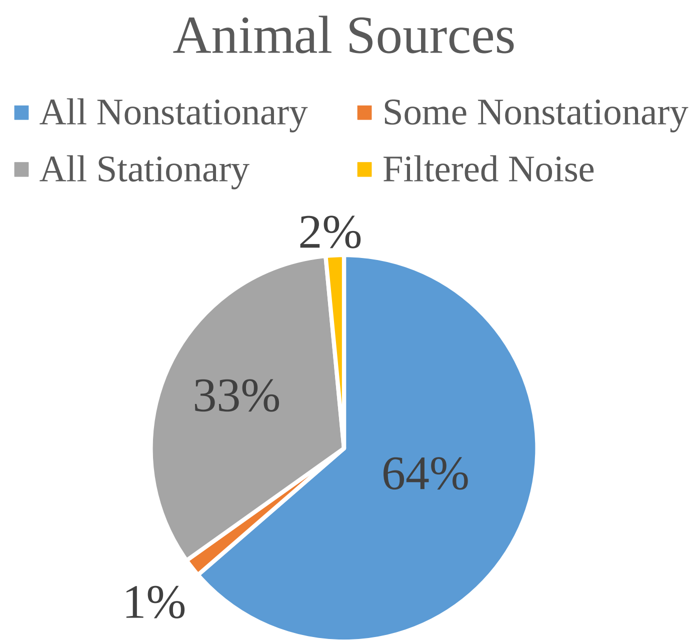
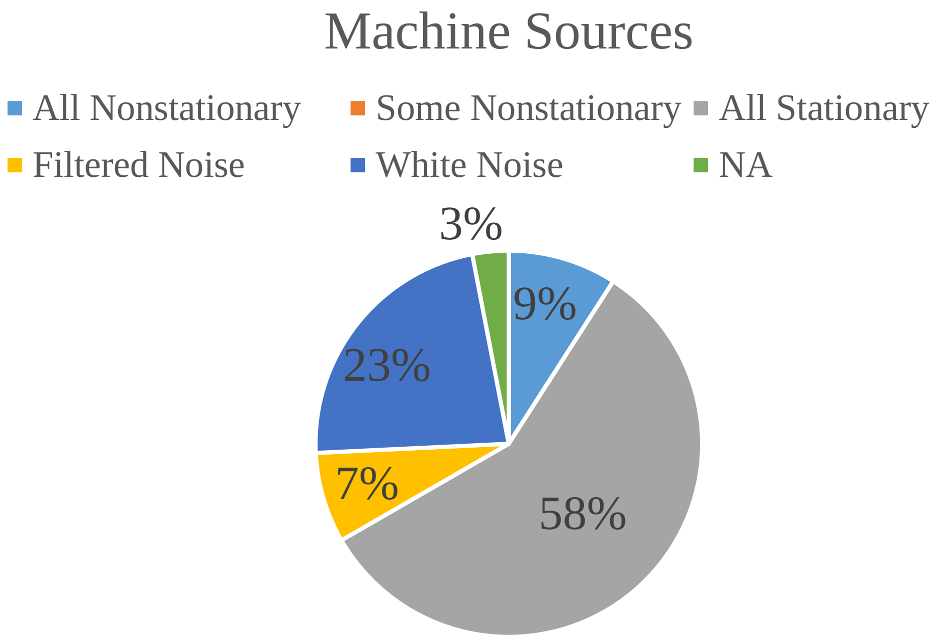
Results

- Vast majority of the animal source vibrations classified as having dominant frequencies
- 64% have dominant frequencies that all moved in time
- 33% have dominant frequencies that are stationary in time



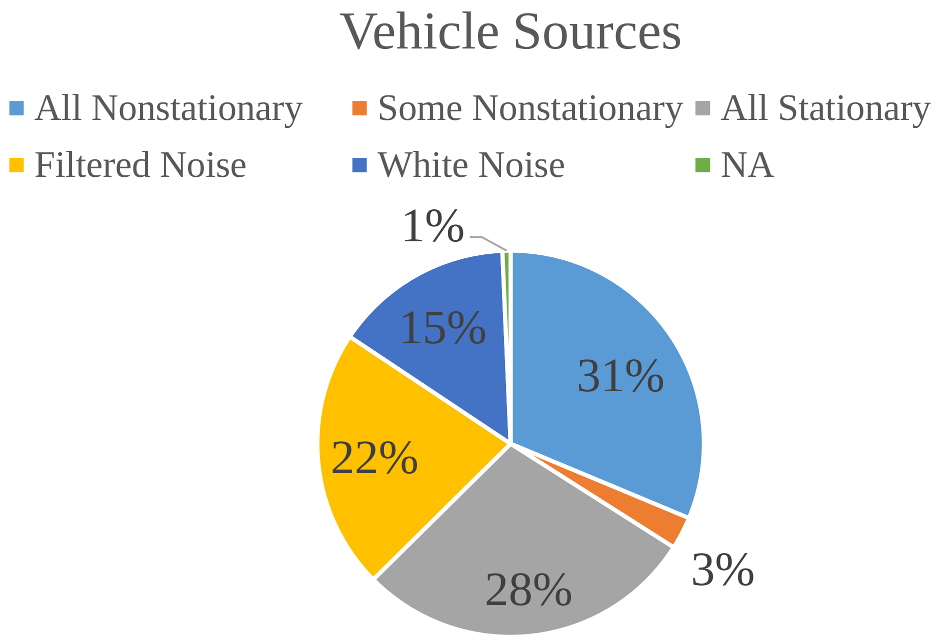
Results

- 58% of machine sources in the study produce stationary dominant frequencies
- 30% of the machine sources produce signals that are best described by some kind of noise



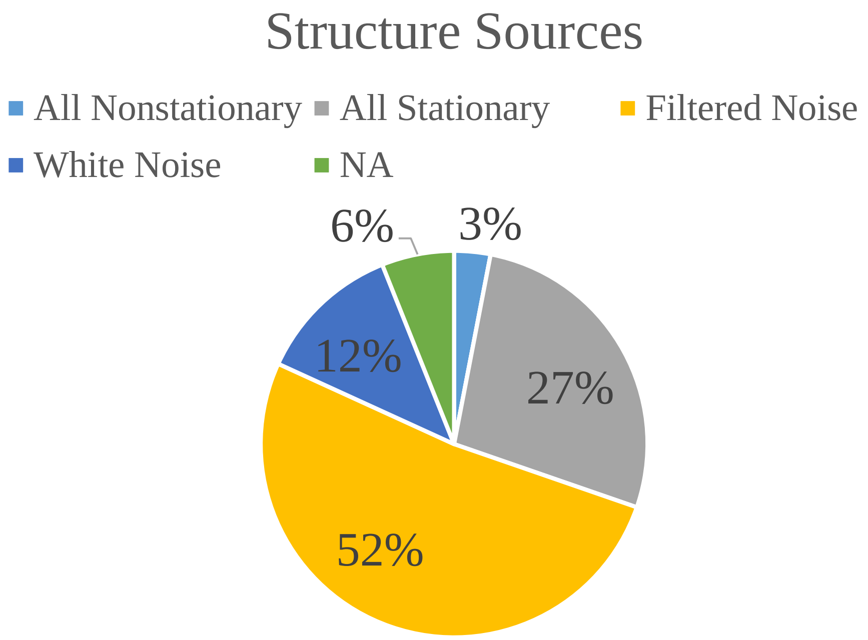
Results

- The vehicle sources in the study represent the most variety in classification
- 53% of the vehicle sources in the study produce signals that are best described by some kind of noise



Results

- 64% of the structure sources in the study produce signals that are best described by some kind of noise
- 27% of the structure sources produce signals with stationary dominant frequencies



Conclusions

- 23% of the signals in the study were classified as having a single dominant, stationary frequency
  - The VDRG model suggests that the upper bound on average power can be achieved by virtue of a linear harvester architecture
  - For these signals, a linear harvester structure is likely the optimal architecture

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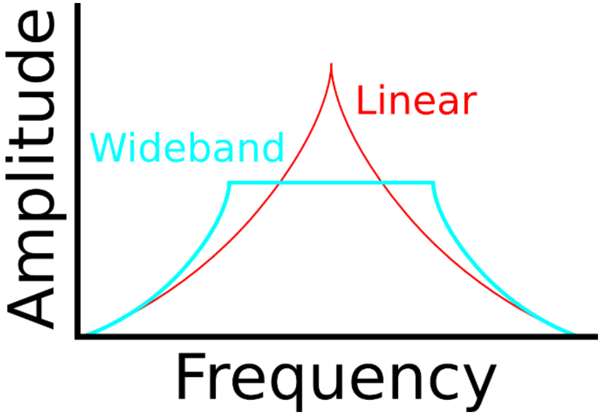
Conclusions

- 53% of signals in the study were classified as…
  1. single dominant nonstationary frequency
  2. filtered noise
  3. multiple dominant stationary frequencies
- Thus, it is reasonable to conclude that wideband harvester architectures could represent a significant improvement over linear architectures in 53% of the cases in the study



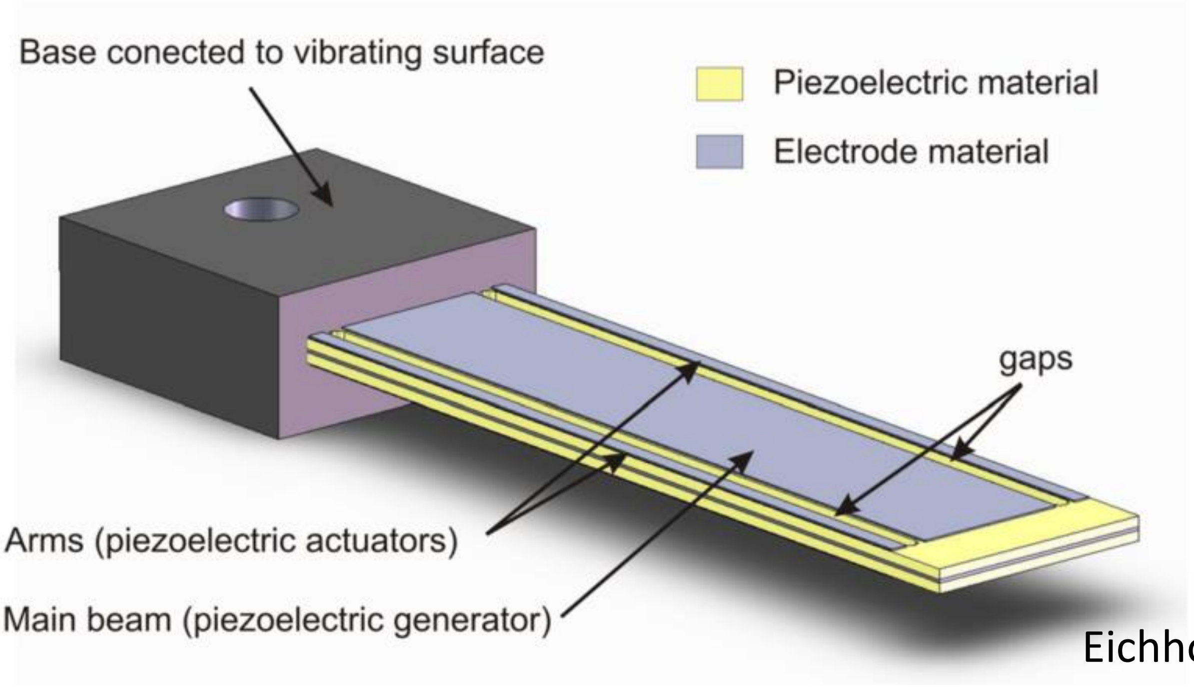
Approaches to Deal with Narrow Bandwidth

Strategy	**Type**	**Tuning Input Required**	**Self-tuning?**
Tunable Resonant	Active	Continuous	Possibly
		Intermittent	Possibly
		Manual	No
	Passive	None	Yes
Multi-modal	Passive	None	Yes
Wideband	Passive	None	Yes

Adapted from:
L. Miller, Vibration Energy Harvesting from Wideband and Time-Varying Frequencies, in Micro Energy Harvesting, Wiley VCH 2016.

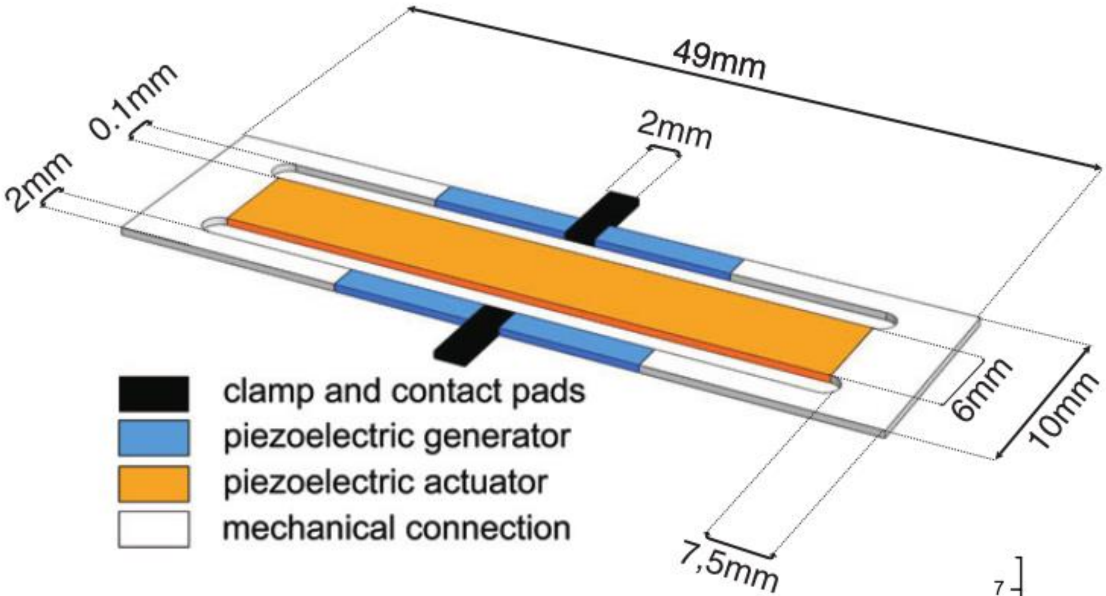
Active Continuous Tunable Harvesters

- Generally have some sort of active control over the effective stiffness
- It's important to note that this approach can easily lead to a negative net power output

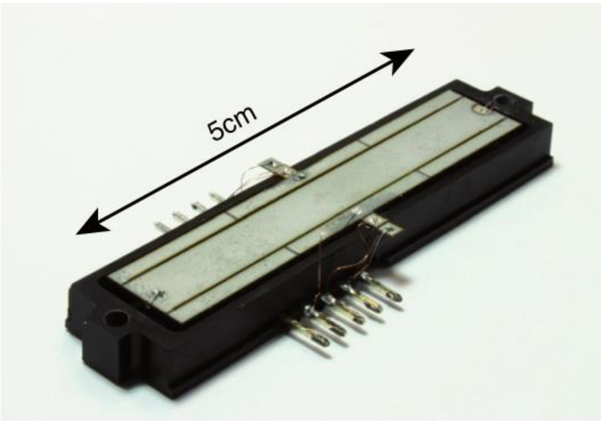


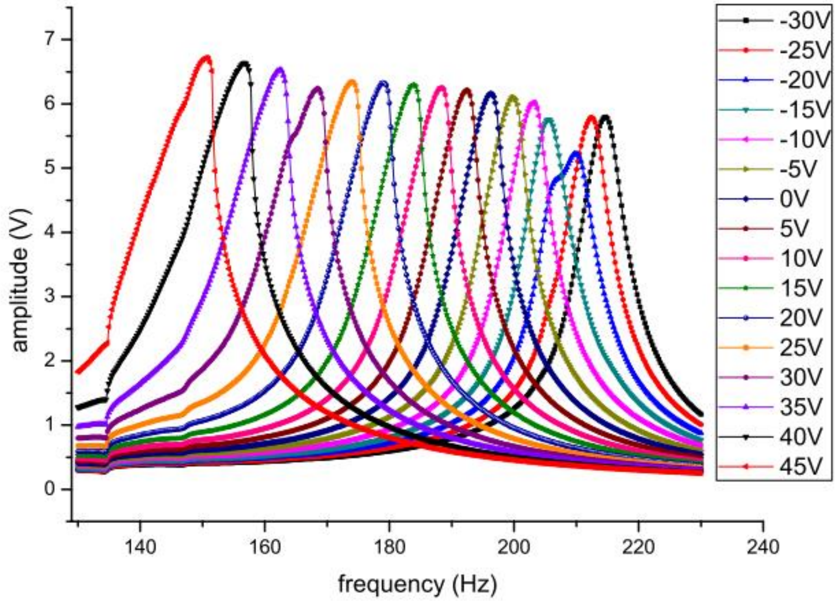
Eichhorn et. al., PowerMEMS 2009

Active Continuous Tunable Harvesters

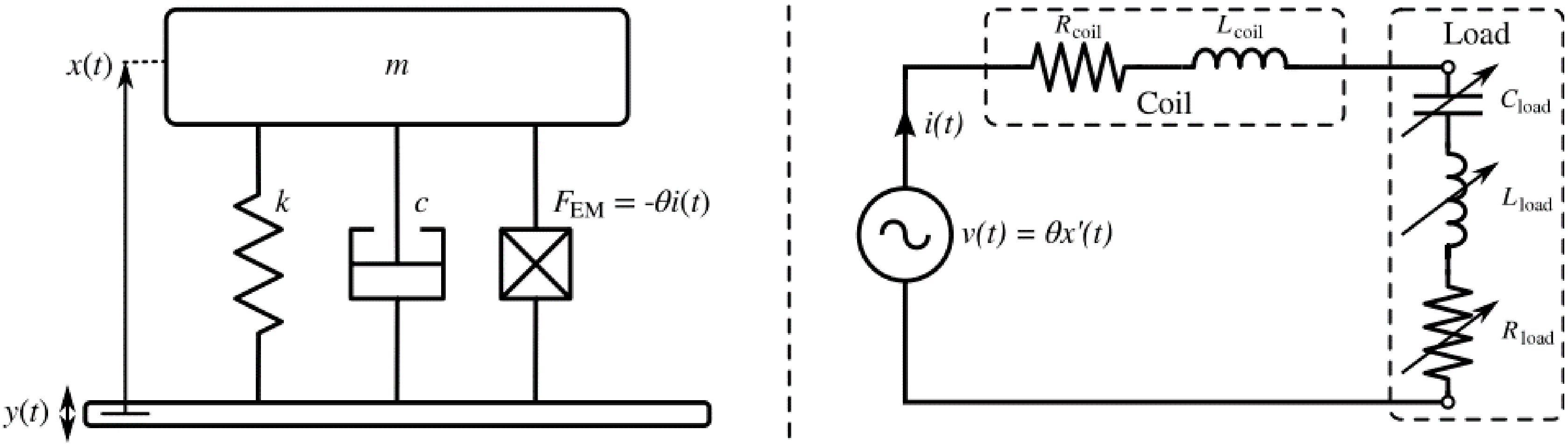


Eichhorn et. al., JM&M 2011





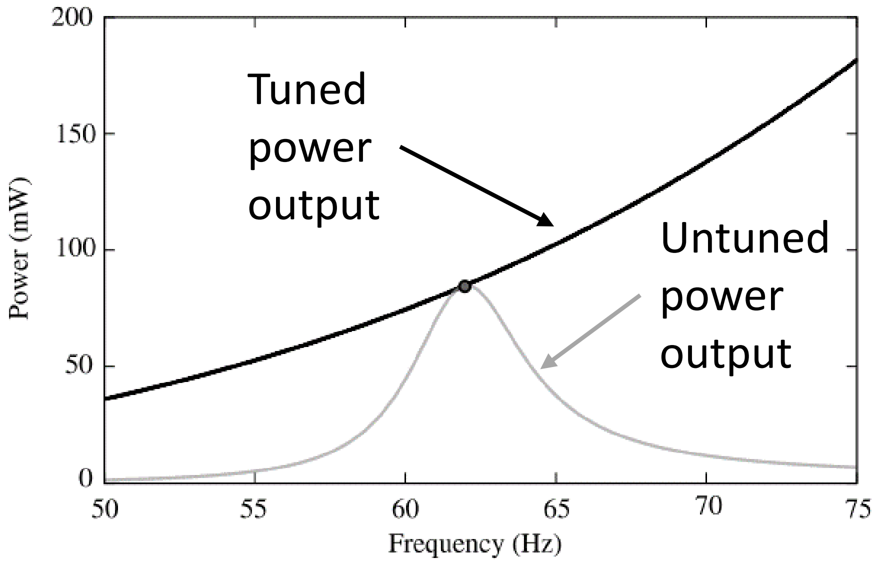
Using Circuits to Tune Resonance

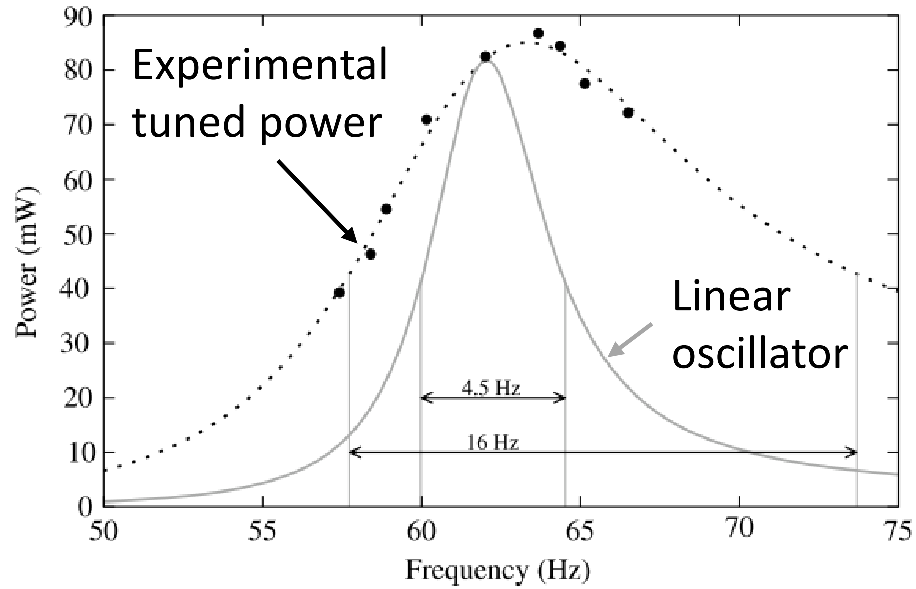


- Schematic model of a linear oscillator based electromagnetic generator
- The system resonance can be altered through controlled reactive circuit load components

Cammarano et. al., Smart Materials and Structures, 2011

Using Circuits to Tune Resonance



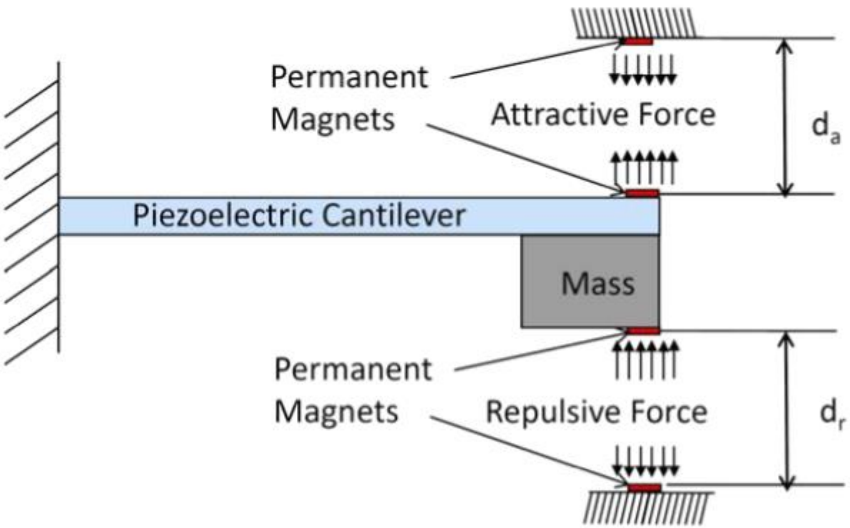


With an idealized system, in theory the works very well.

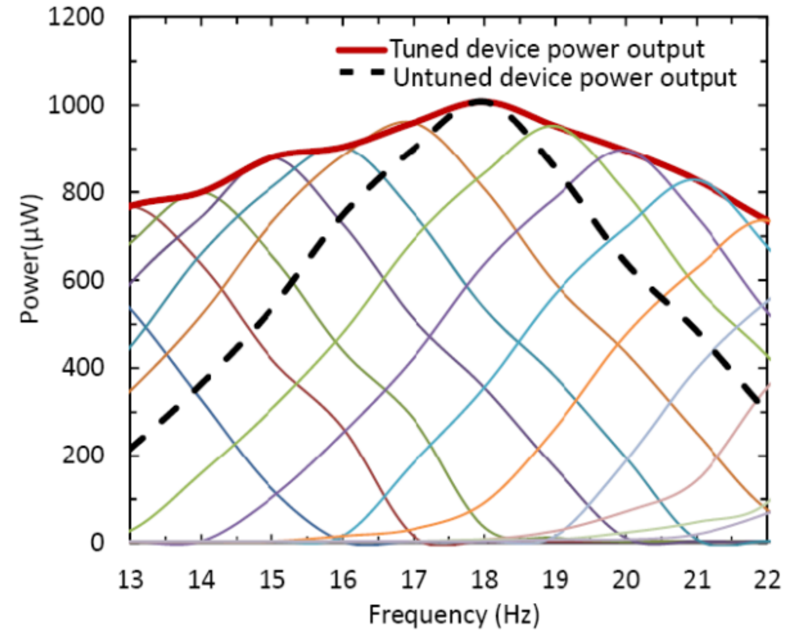
In practice the tuning range is limited by the need to produce extremely large reactive loads.

Cammarano et. al., Smart Materials and Structures, 2011

Intermittent Tunable Harvesters

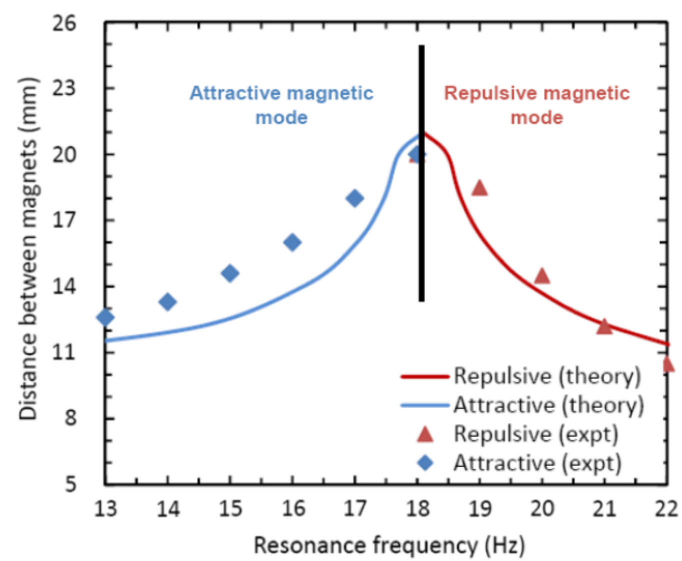


Challa et. al., SMS, 2011



Effective stiffness tuned by controlling distances d_a and d_r.

This is “intermittent” because the magnets can be positioned, and then when resonance is achieved, the positioning actuators can be turned off.



Passive Self-tuning Devices

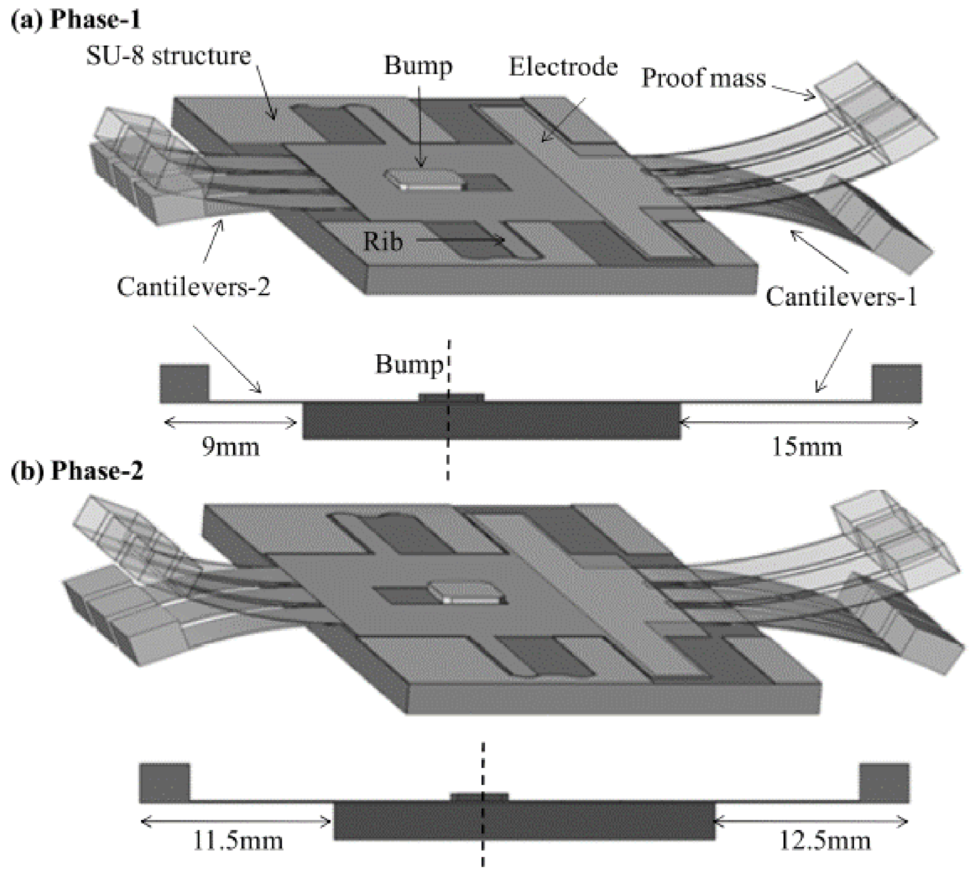
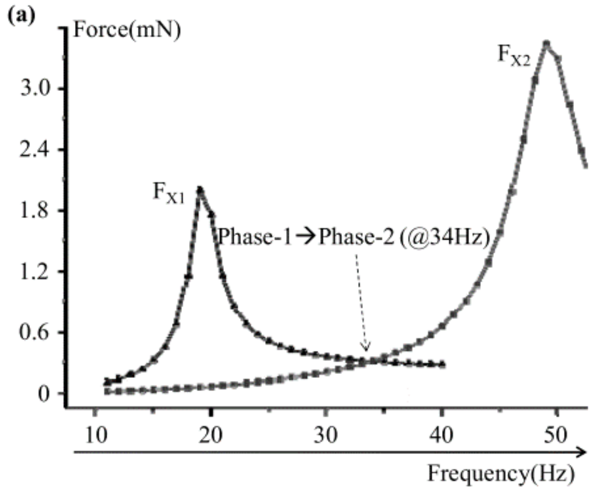
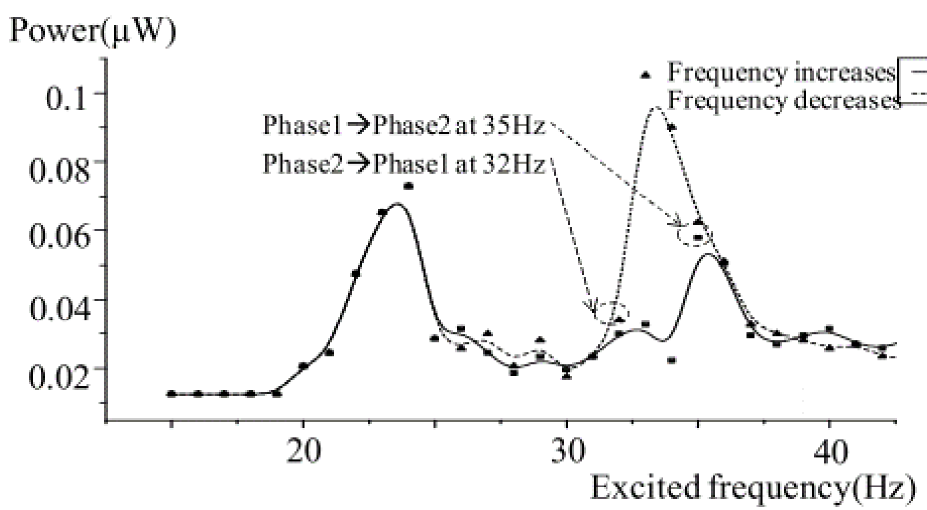


Figure 1. Schematic view of the proposed self frequency tunable energy harvester as (a)Phase-1 and (b)Phase-2

Jo et. al., Transducers / Eurosensors, 2011

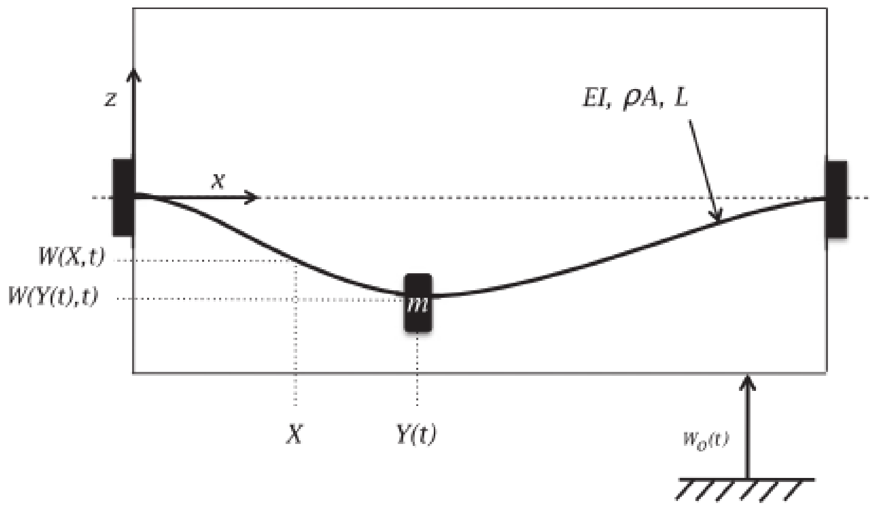
Passive Self-tuning Devices

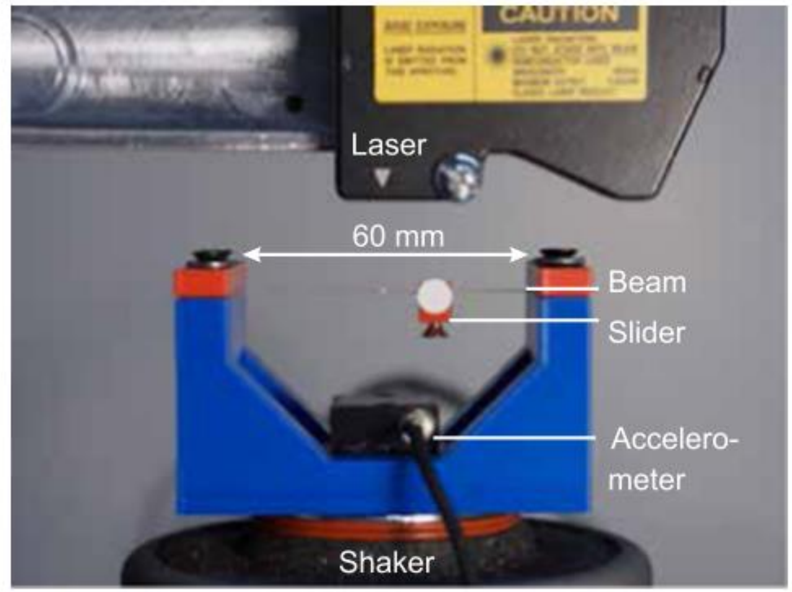




Jo et. al., Transducers / Eurosensors, 2011

Passive Self-Tuning Devices

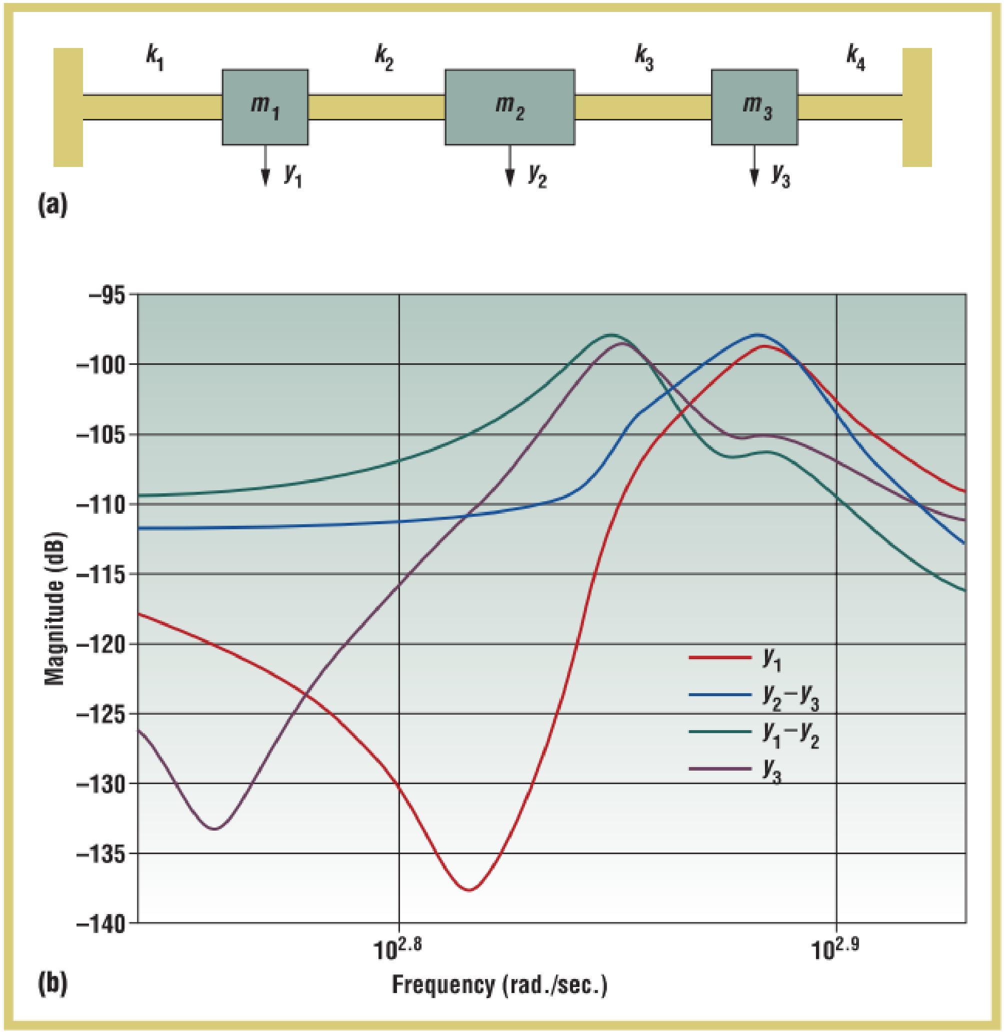




- Researchers at Berkeley have shown that under certain conditions a sliding proof mass on a beam will passively slide to a position that achieves resonance

Miller et. al., Journal of Sound and Vibration, 2013

Multi-mode Harvesters



Roundy et. al., Pervasive Computing, 2005

Wideband Harvesters – Nonlinear Stiffness

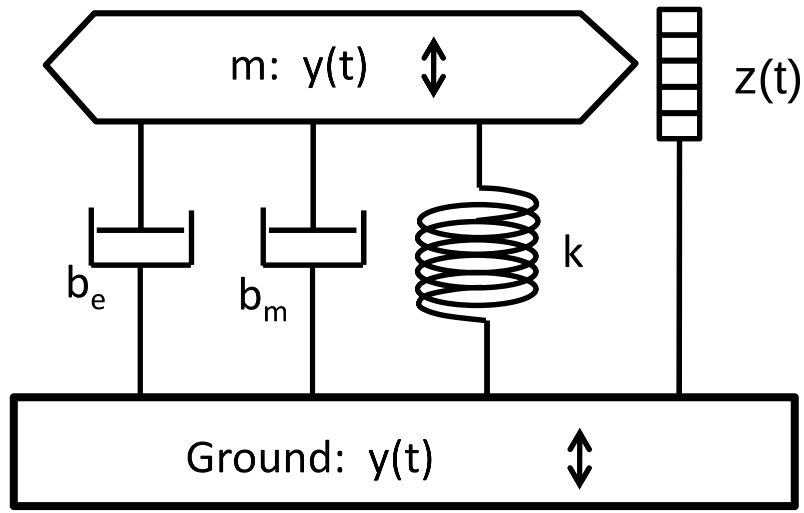
Normally we model the spring force of an oscillator based harvester as $F = kz$, which results in a narrowband resonance at

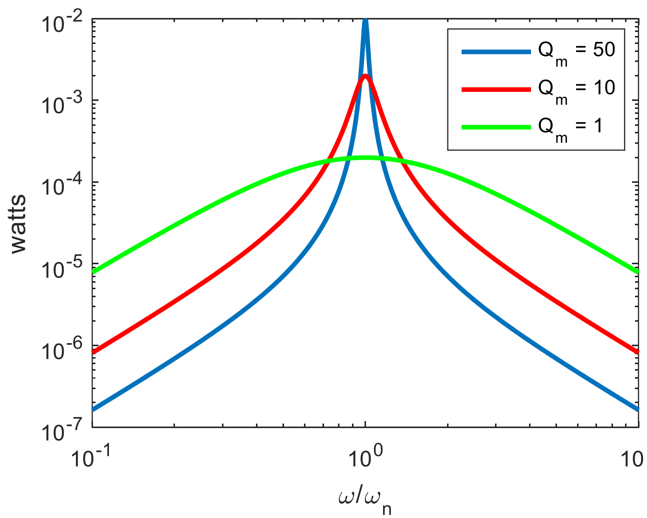
$\omega_n = \sqrt{\frac{k}{m}}$, and the following governing equation:

$$m\ddot{z} + b\dot{z} + k_1 z = -mA$$

And displacement magnitude given by:

$$Z(j\omega) = \frac{1}{(1 - r^2) + j2\zeta r} \frac{A}{\omega_n^2}$$





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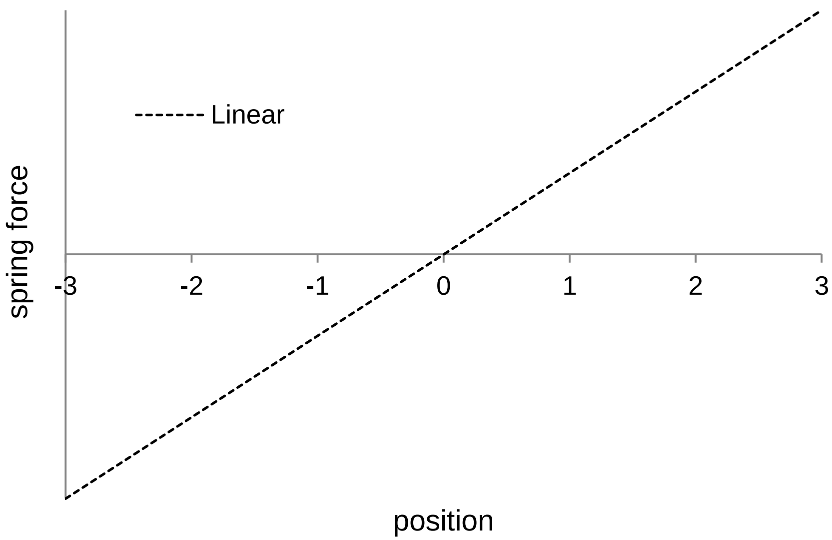
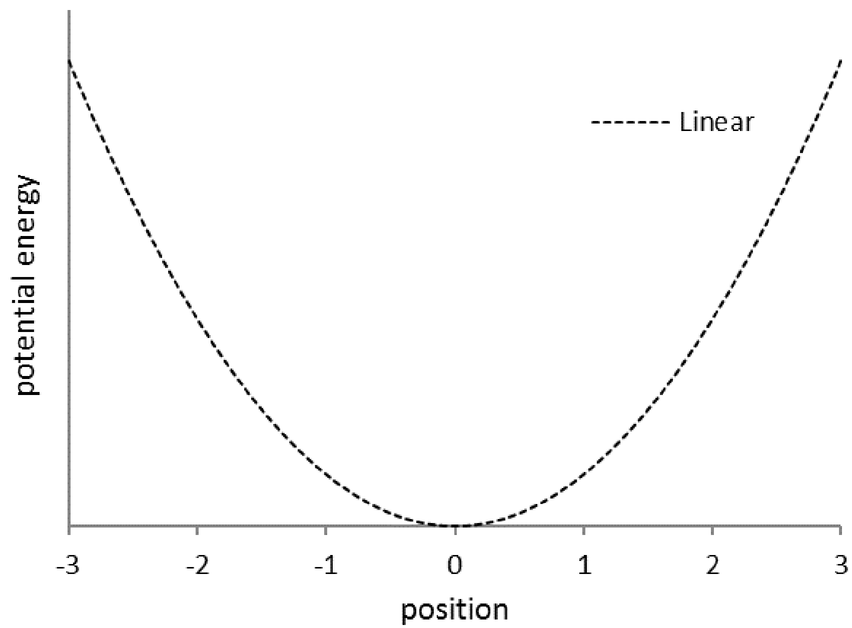
Wideband Harvesters – Nonlinear Stiffness

This leads to the following spring force and stored energy graphs



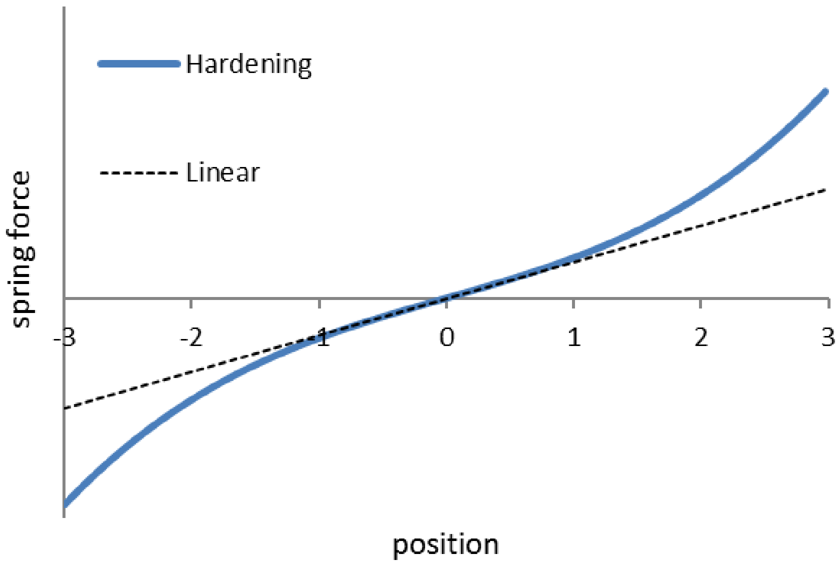


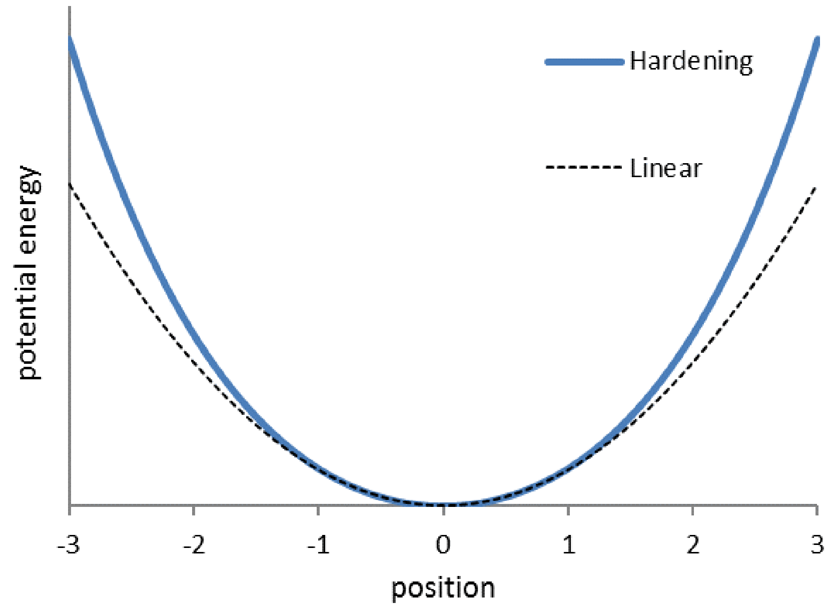
Wideband Harvesters – Nonlinear Stiffness

Nonlinearities in the effective stiffness function, usually modeled by the Duffing equation, result in some very useful characteristics for harvesting

$$m\ddot{z} + b\dot{z} + \alpha z + \beta z^3 = -mA$$

If **$\alpha > 0$,and $\beta > 0$**, the system is called a **hardening** oscillator.





Wideband Harvesters – Nonlinear Stiffness

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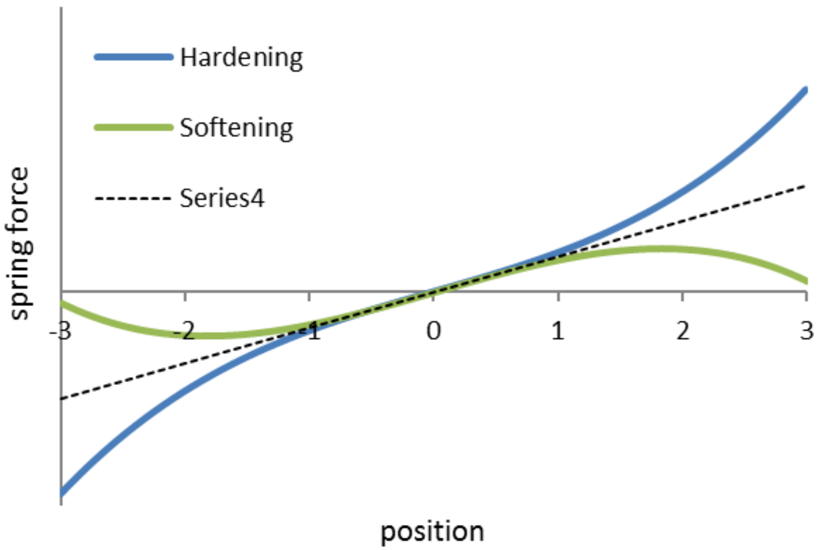
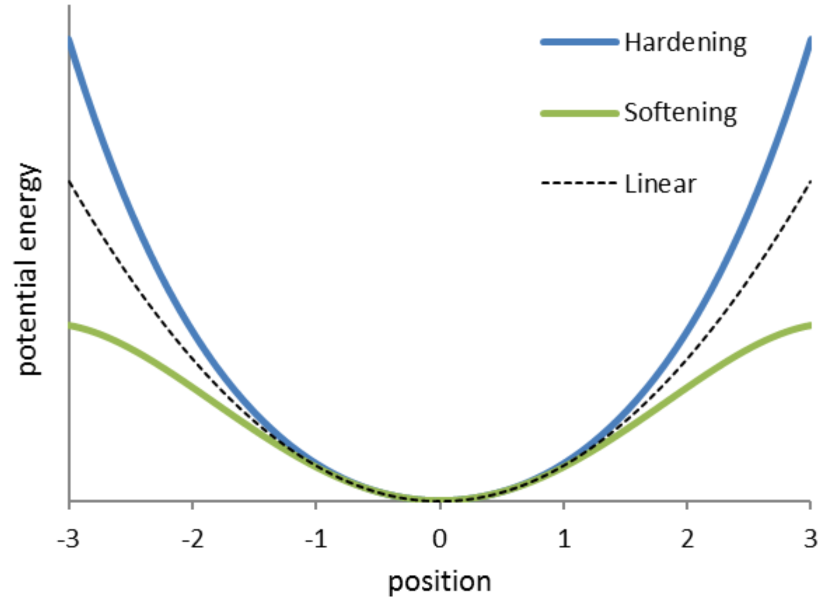
$$m\ddot{z} + b\dot{z} + \alpha z + \beta z^3 = -mA$$

If $\underline{\boldsymbol{\alpha > 0} \text{ ,and } \boldsymbol{\beta < 0}}$, the system is called a **softening** oscillator.



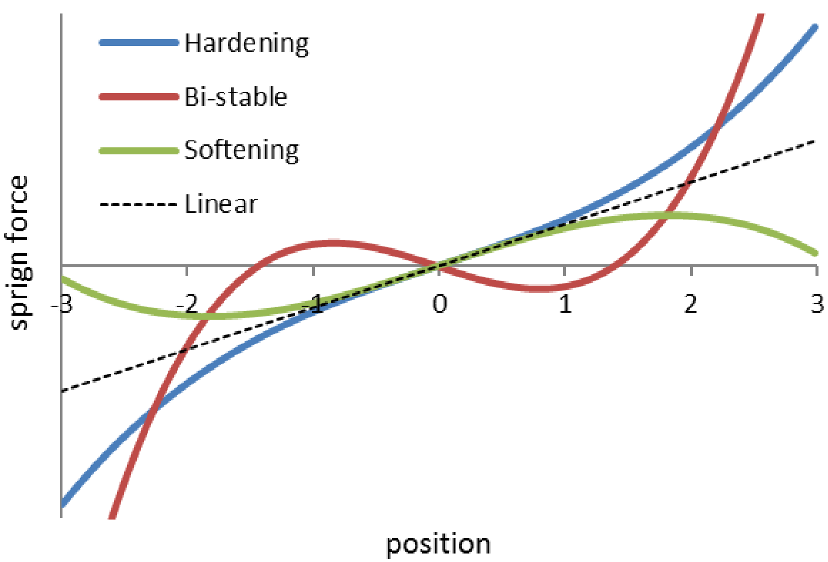


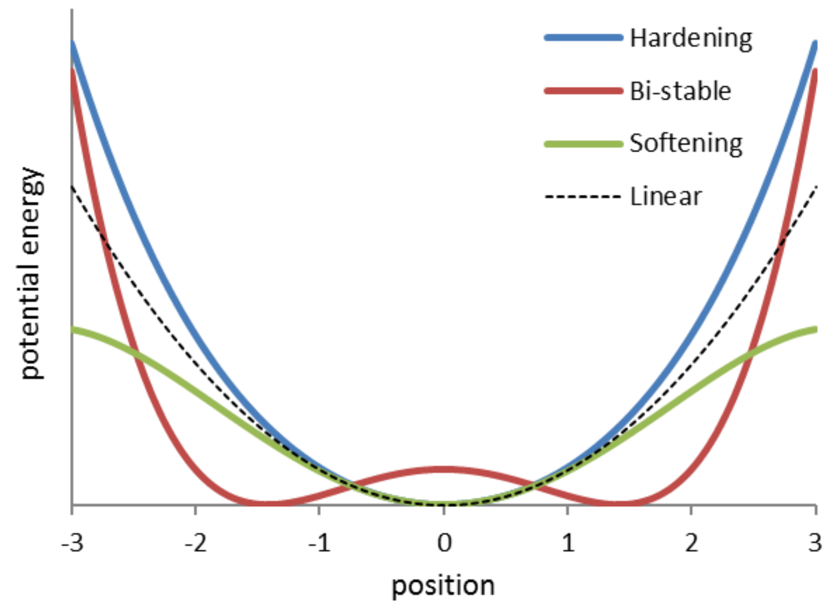
Wideband Harvesters – Nonlinear Stiffness

Nonlinearities in the effective stiffness function, usually modeled by the Duffing equation, result in some very useful characteristics for harvesting

$$m\ddot{z} + b\dot{z} + \alpha z + \beta z^3 = -mA$$

If $\boldsymbol{\alpha < 0}$ **,and** $\boldsymbol{\beta > 0}$, the system is called a **bi-stable** oscillator.





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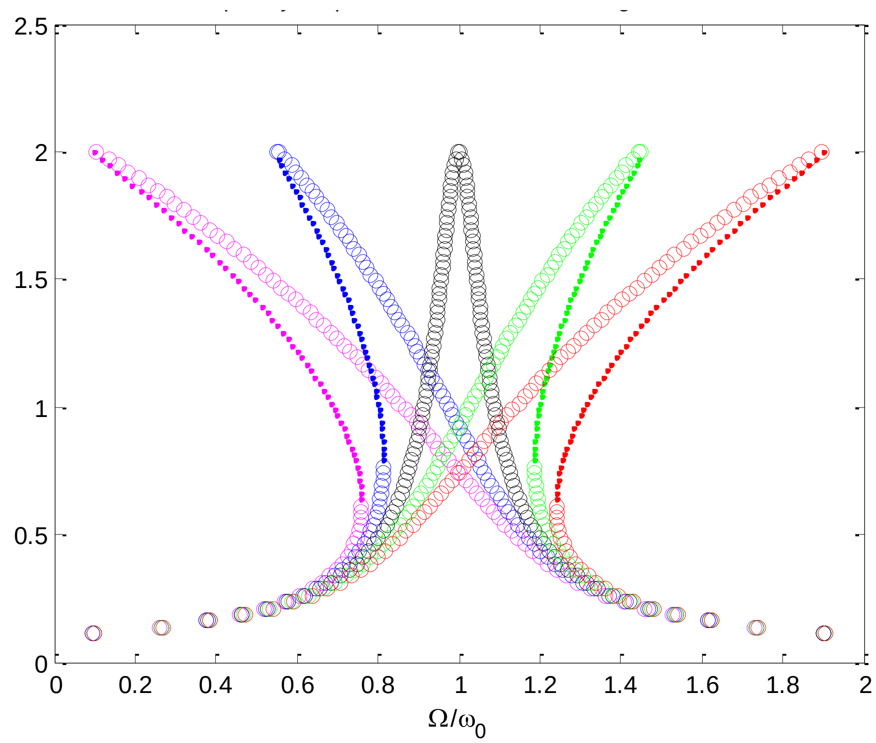
Wideband Harvesters – Nonlinear Stiffness



- The frequency spectrum from all types of duffing oscillators has a wider band than linear oscillators
- Softening and hardening frequency spectra can be directly calculated
- Bi-stable behavior is more complex

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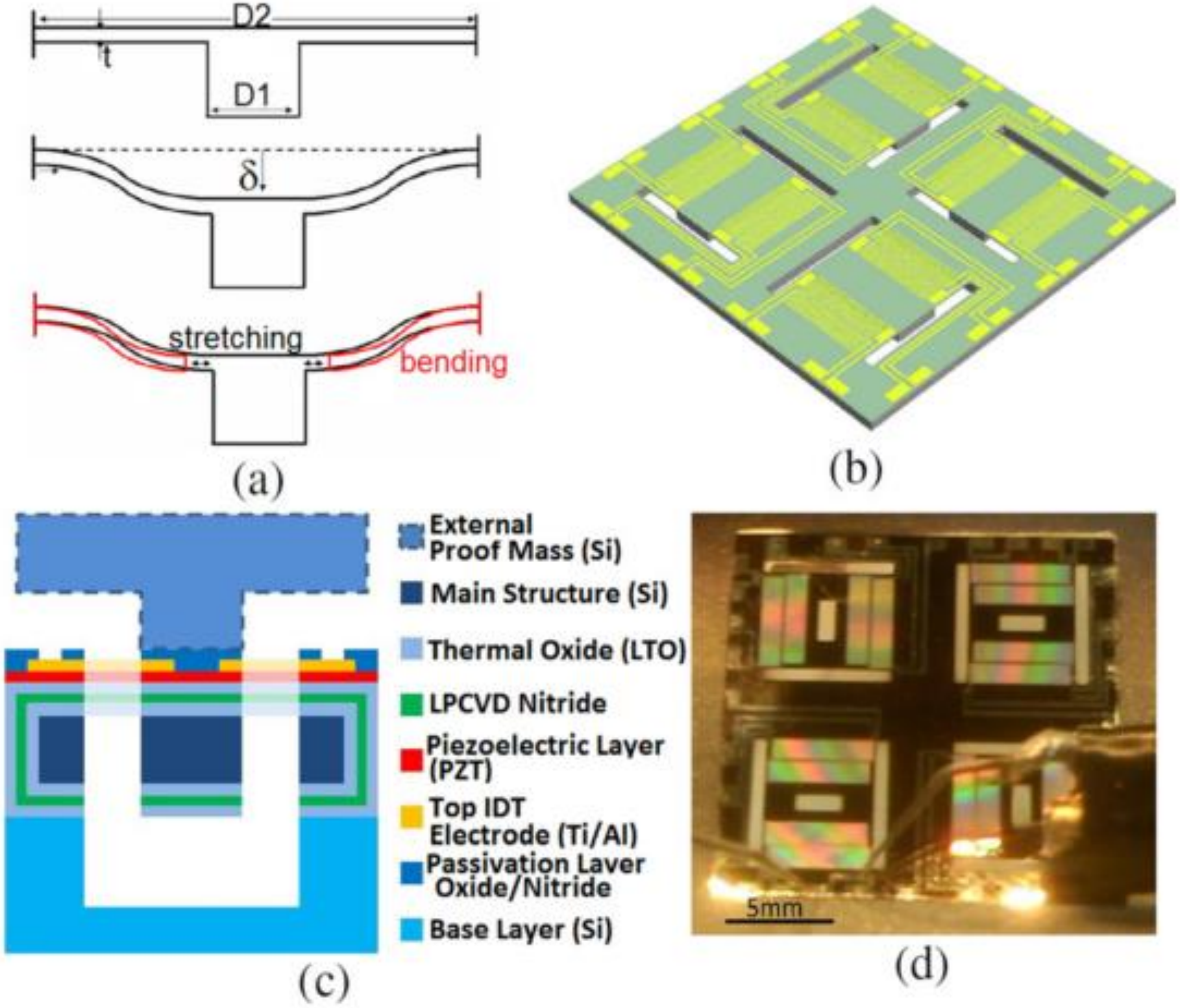
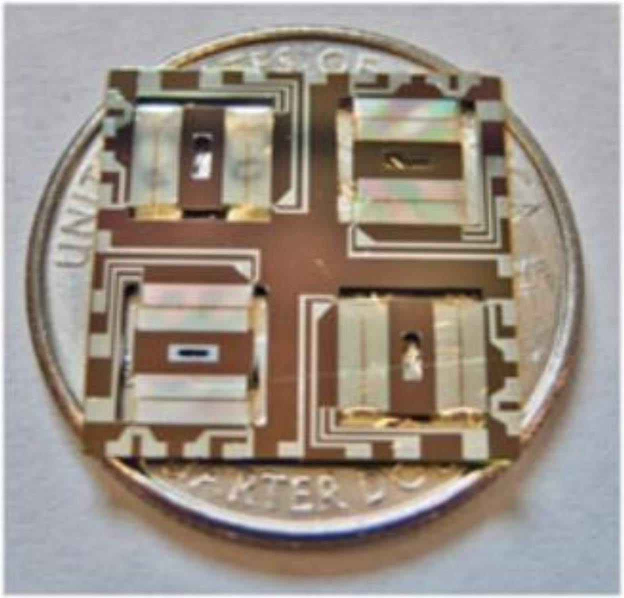
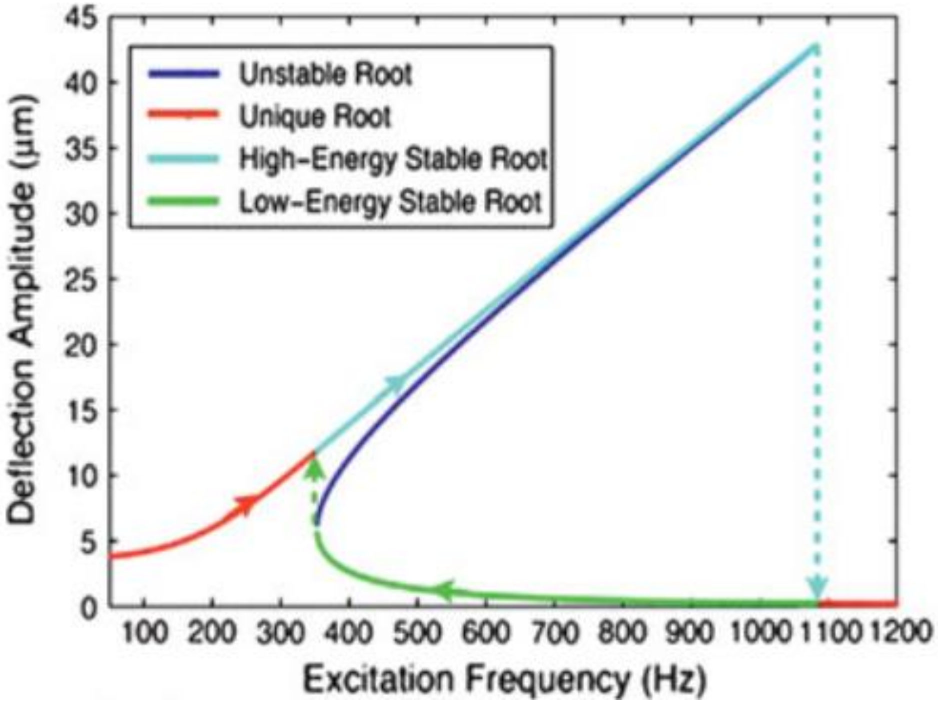
Hardening



Hajati and Kim, APL, 2011

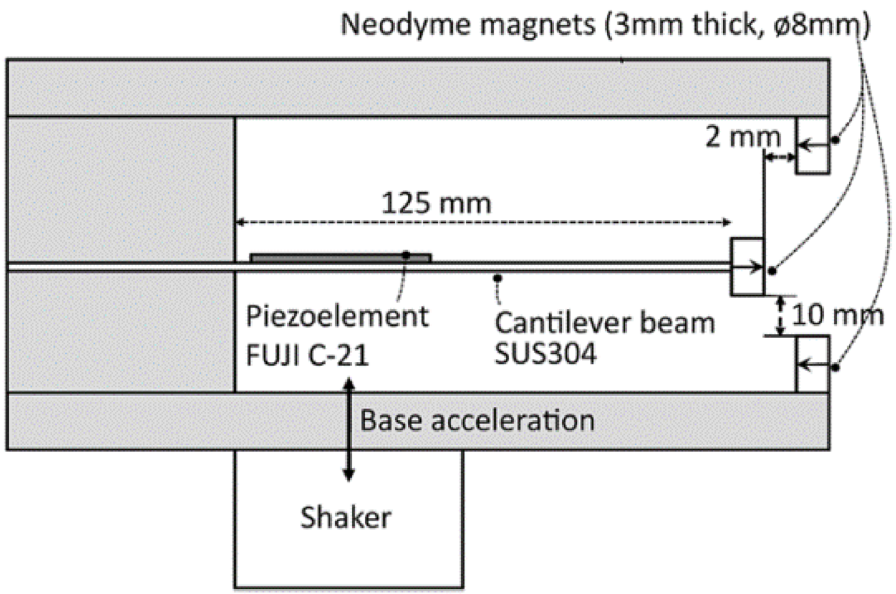
Hardening

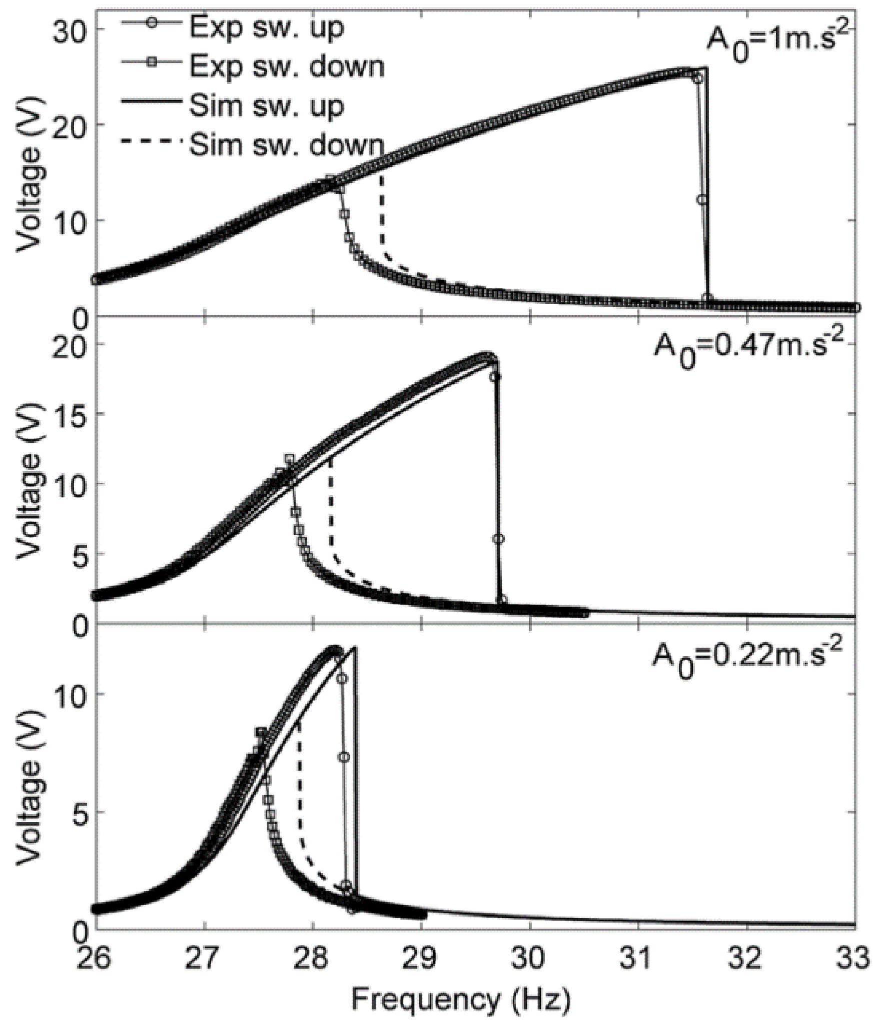




Kim et. al. MRS Bulletin, 2012

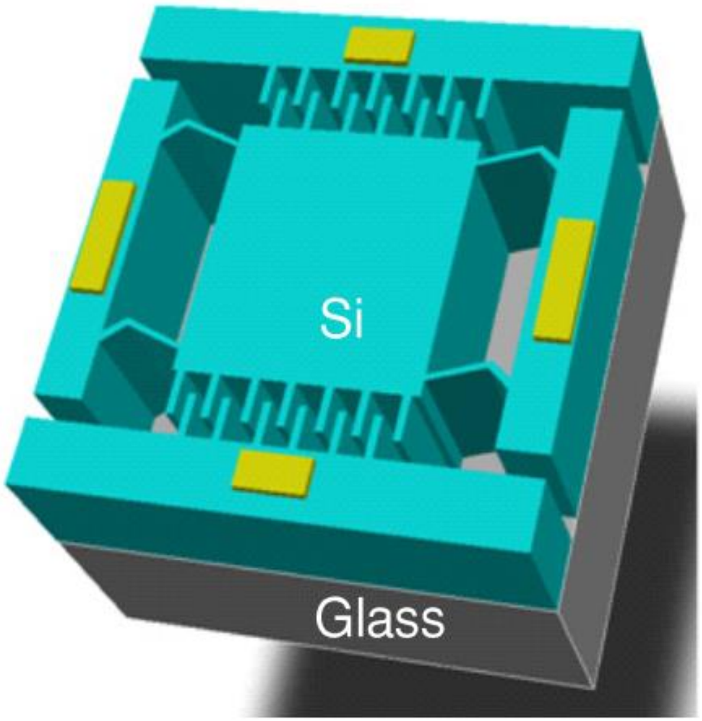
Hardening

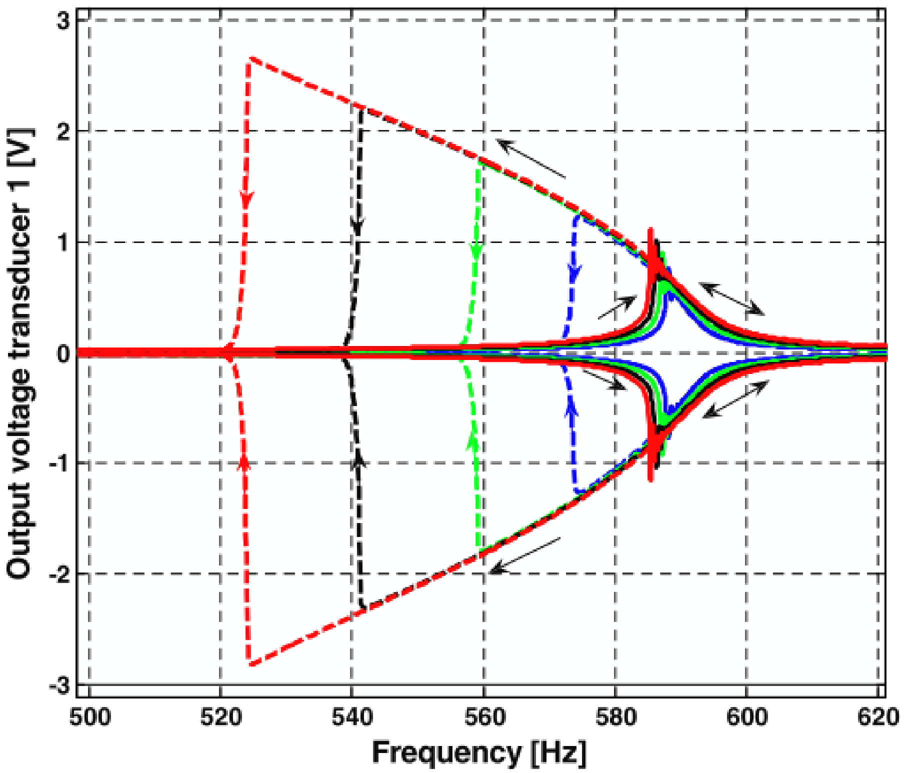




Sebald et. al. SMS, 2010

Softening





Nguyen et. al. JM&M, 2010

Bi-stable

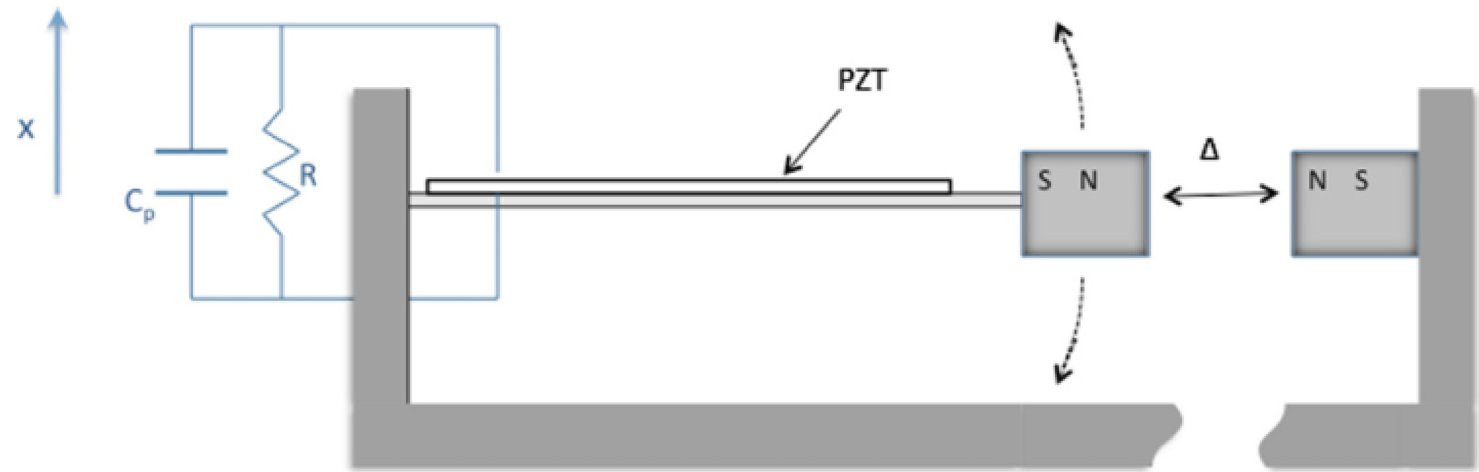
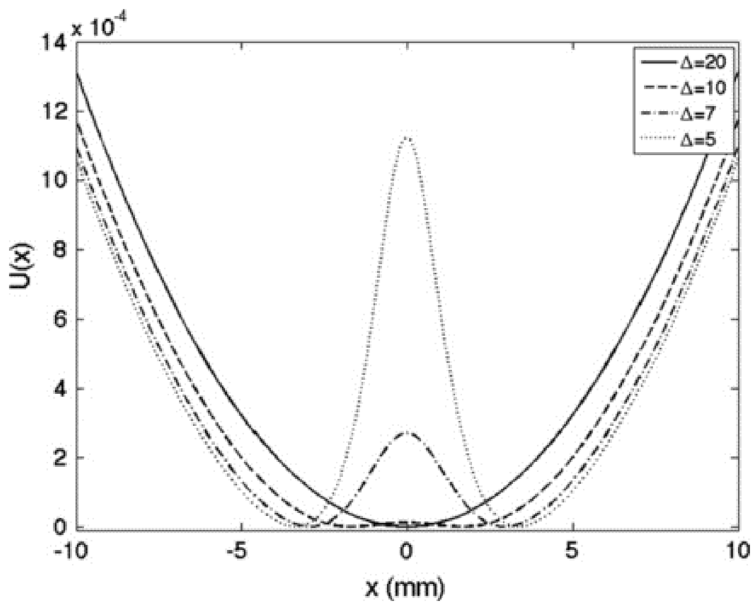


Fig. 1. Schematic of the bistable harvester considered.



Vocca et. al. Applied Energy, 2010

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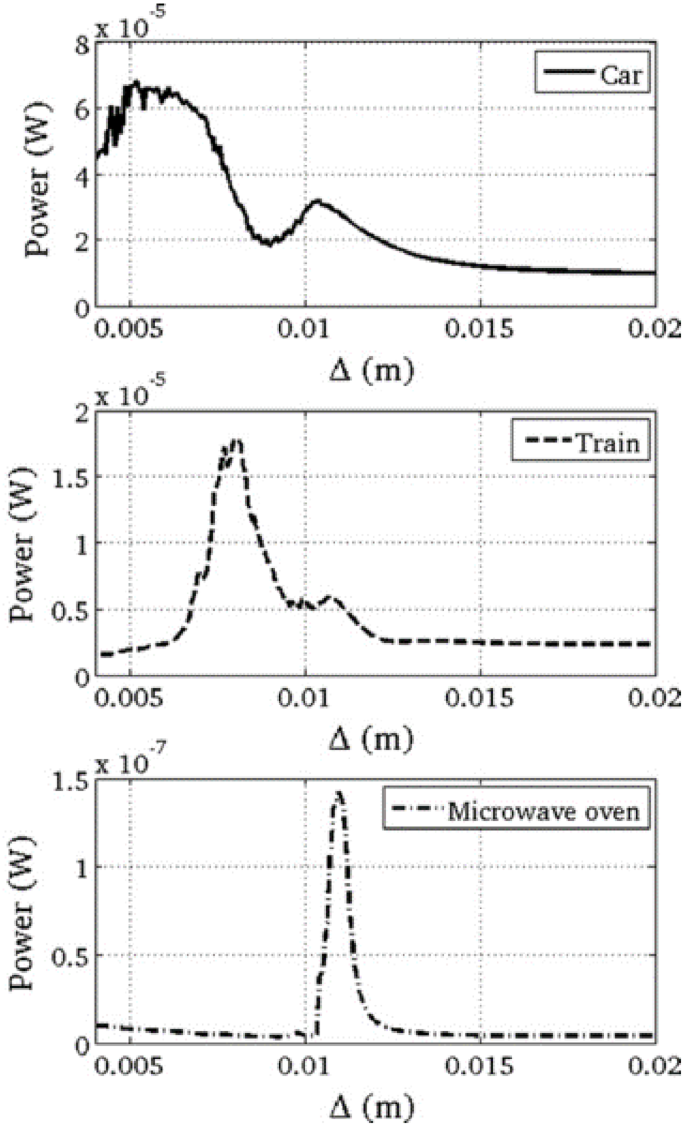
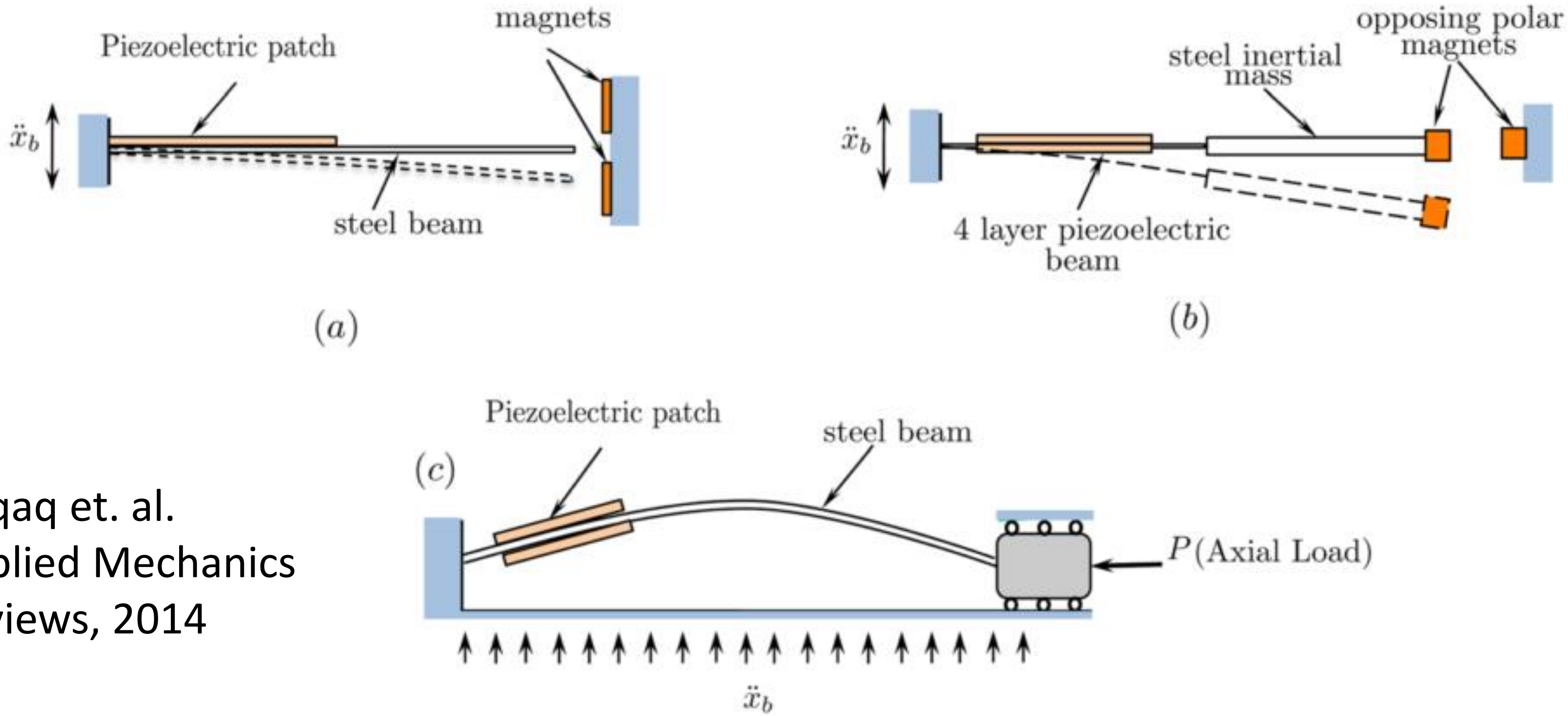
Bi-stable



- Power output increased from between 5.5X and 34.4X by using a bi-stable oscillator for the three cases tested, Car, Train, and Microwave oven
- Power output is very sensitive to the distance of the magnet, or in other words, the shape of the potential energy function

Vocca et. al. Applied Energy, 2010

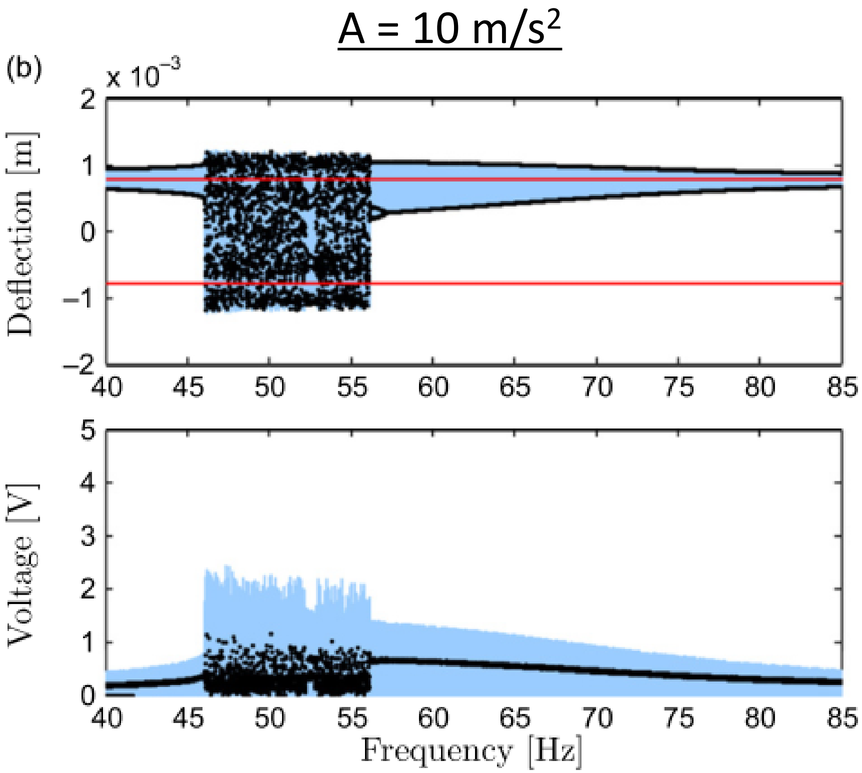
Bi-stable

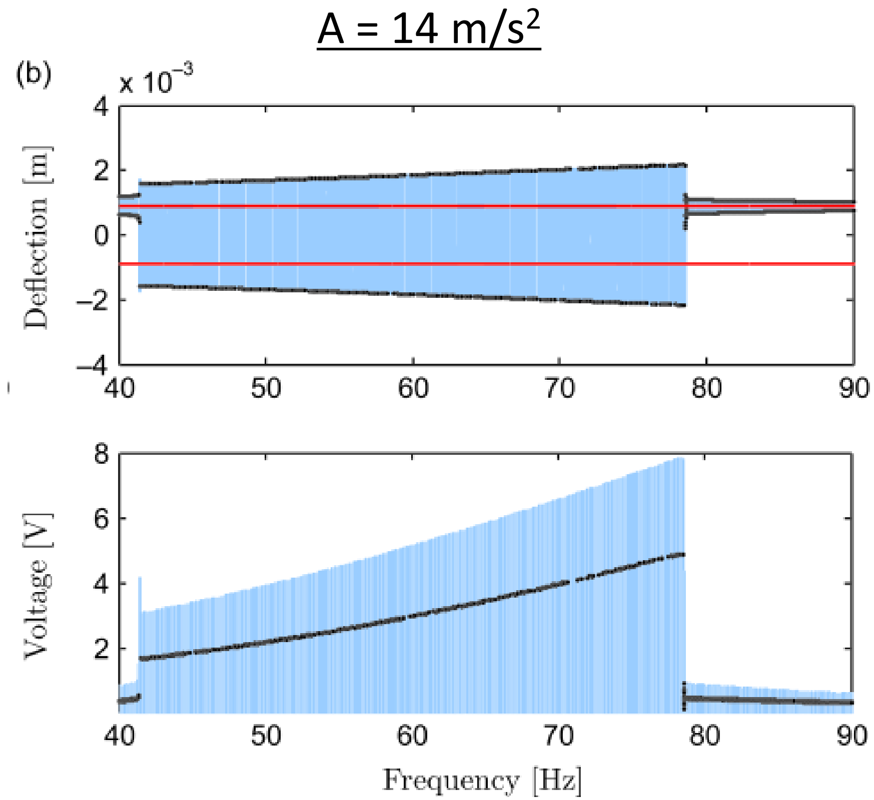


Daqaq et. al.
Applied Mechanics
Reviews, 2014

- Many different configurations possible to create bi-stable stiffness functions

Bi-stable



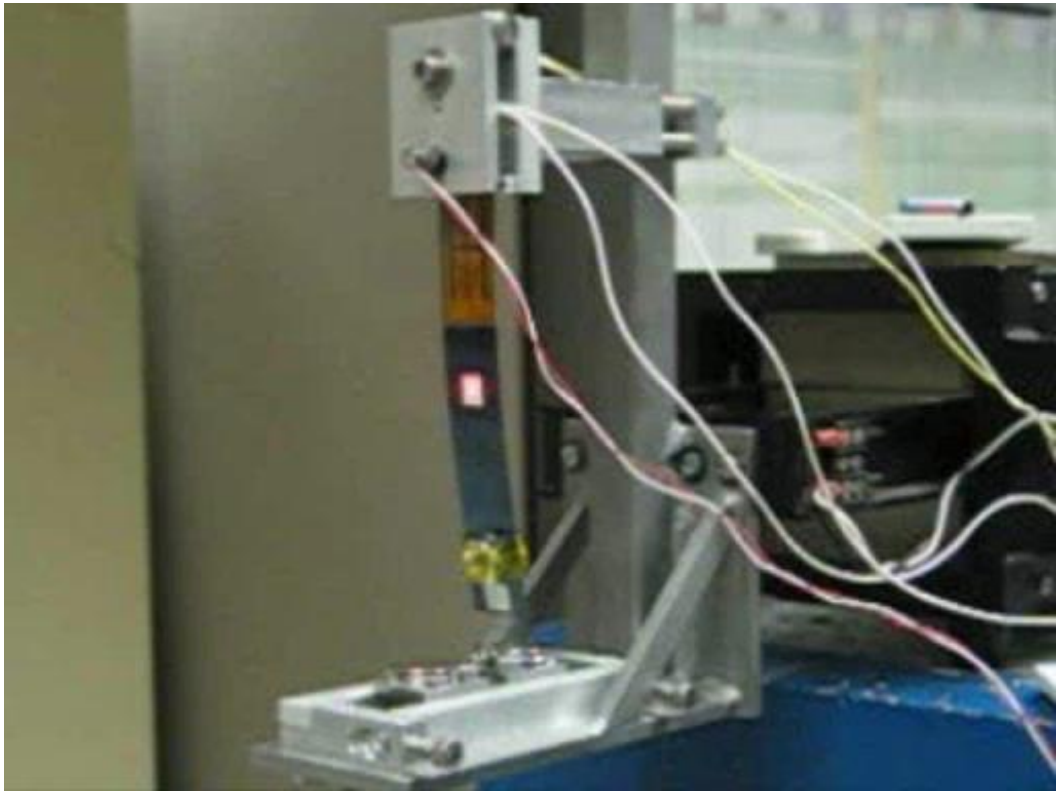


Daqaq et. al. Applied Mechanics Reviews, 2014

Chaotic behavior between 45 and 55 Hz, meaning that sometimes proof mass jumps to the other well. Outside of this range, only inner-well oscillations

Stable intra-well oscillations over most of the frequency excitation range.

Bistable Piezomagnetoelastic Structure for Broadband Energy Harvesting



Courtesy of Prof. Alper Erturk, Georgia Tech Univ.

Continuous Tunable with Nonlinearity

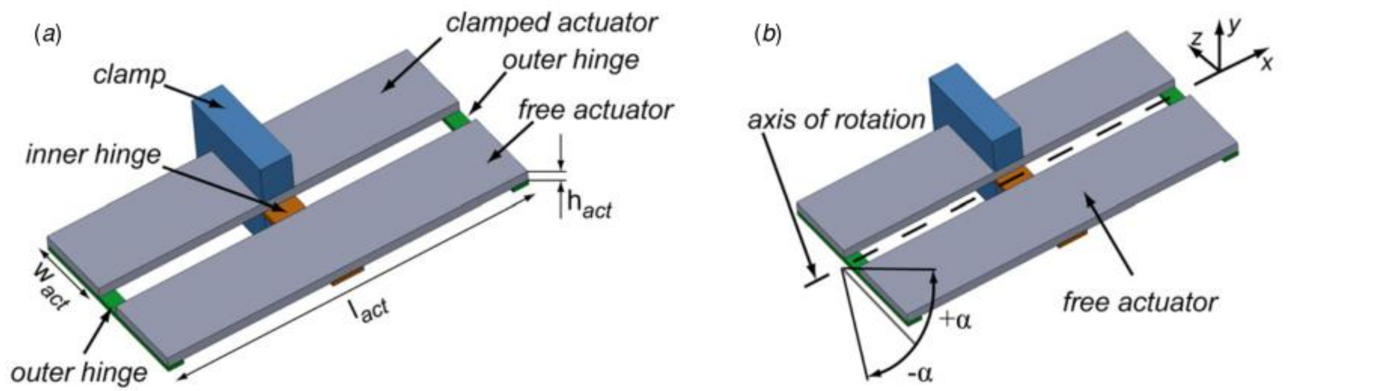


Figure 1. (*a*) Tunable resonator with one clamped and one free actuator mounted with three hinges. (*b*) The free actuator swings around the axis of rotation with a deflection angle α.

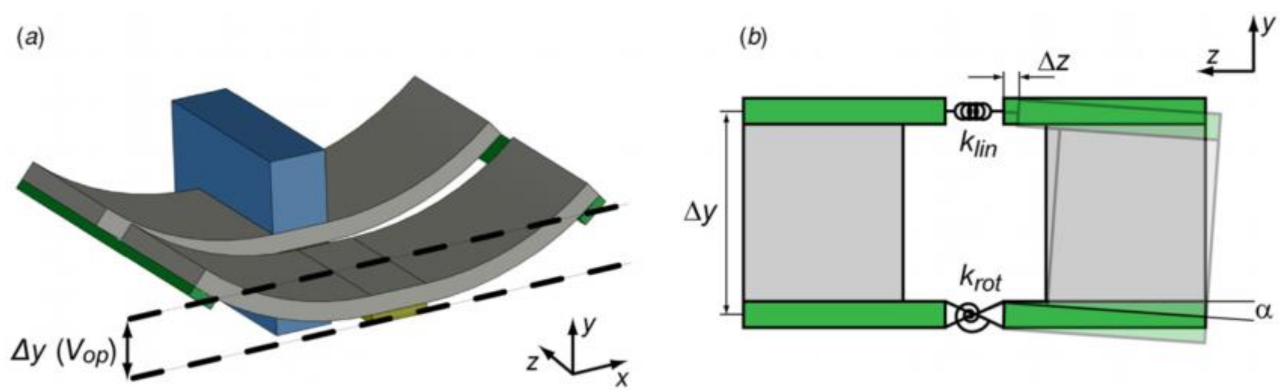


Figure 2. (*a*) Schematic cross section with applied tuning voltage. Both endings of the actuators are deflected by $\Delta y(V_{op})$. (*b*) Side view of the resonator.

Peters et. al., JM&M, 2009

Tunable with Nonlinearity

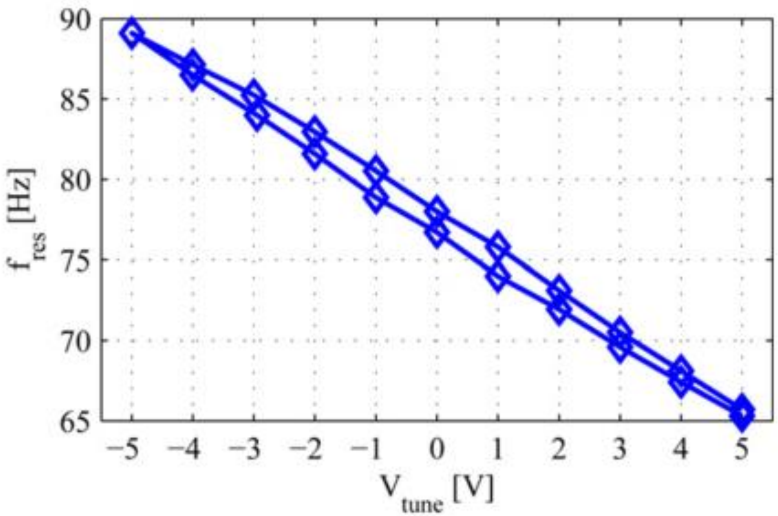
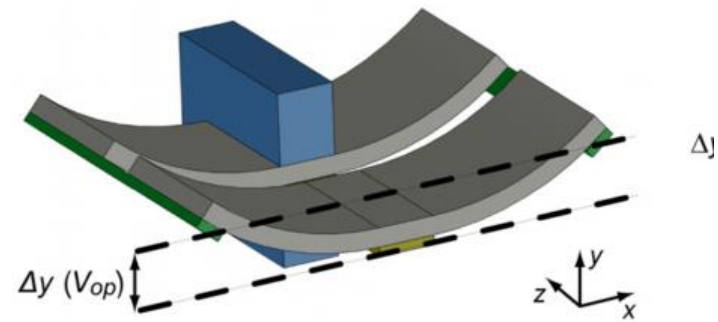


Figure 12. Measured resonance frequency versus applied tuning voltage (PL140).

Peters et. al., JM&M, 2009



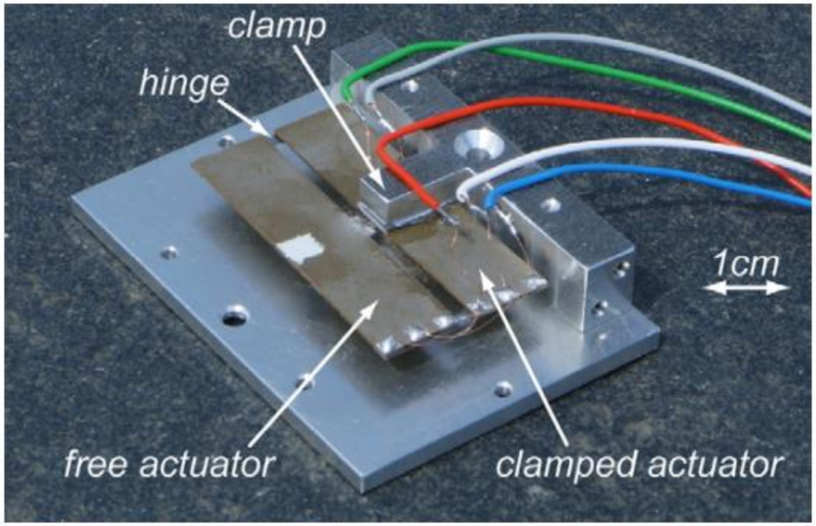
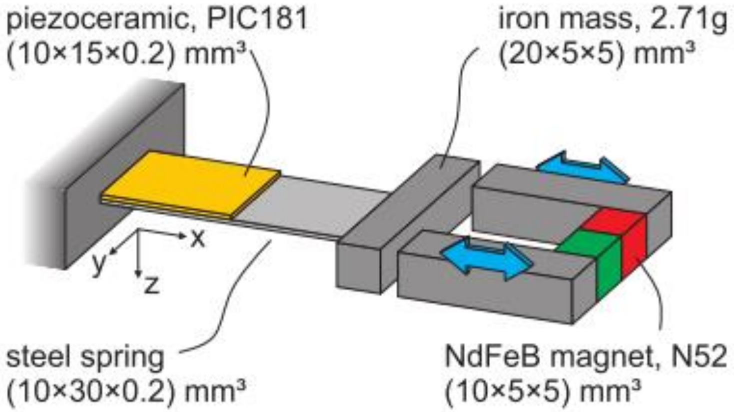
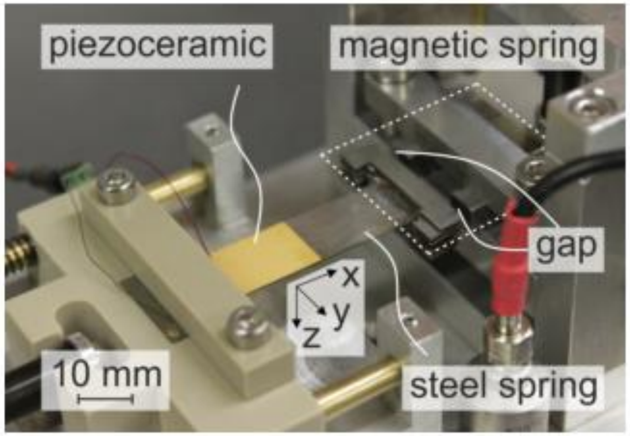


Figure 10. Photograph of the electrically tunable resonator with the wires for the electric tuning and the clamp support.

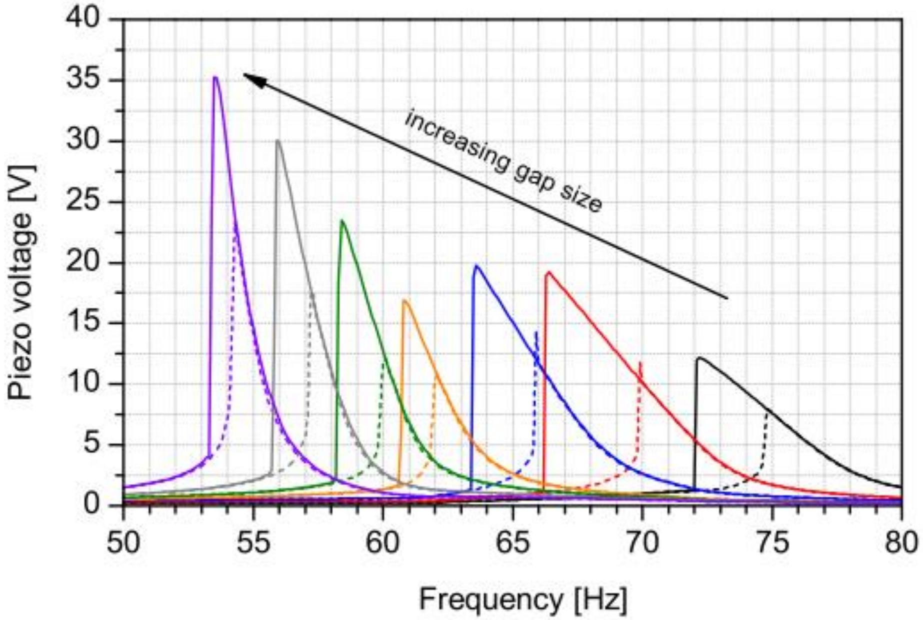
Tunable with Nonlinearity

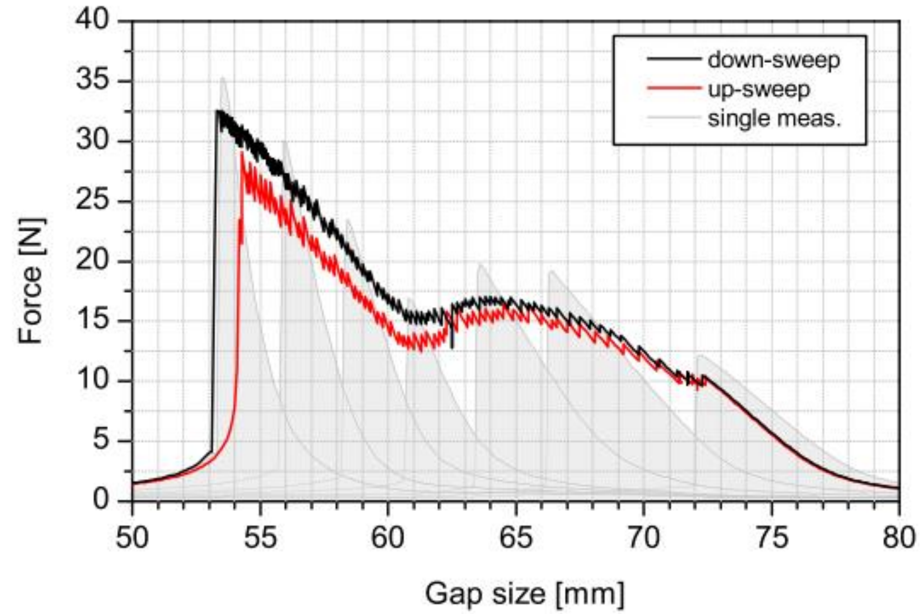




Neiss et. al., PowerMEMS, 2014

Tunable with Nonlinearity





Neiss et. al., PowerMEMS, 2014

- A phase angle based controller combines the benefits of nonlinearity (softening in this case) and

When is Nonlinearity Useful?

- Beeby et. al. studied 4 specific signals collected as part of the Energy Harvesting Network (http://eh-network.org/) and white noise
  - Diesel ferry engine
  - Combined heat and power pump
  - Petrol car engine
  - Helicopter
- Studied them specifically for 3 types of harvesters
  - Linear oscillator
  - Bi-stable
  - Duffing type nonlinear (they specifically studied softening oscillators)
- Conclusion:
  - Bi-stable has the lowest power output except for a white noise source, where it has the highest
  - For single peak, narrow band, excitations, linear harvesters are best (unsurprising)
  - For single peak, wideband (i.e. filtered noise) linear and nonlinear Duffing (not bi-stable) harvesters perform similarly
  - For multiple peaks, if the Duffing bandwidth can cover both peaks, the Duffing harvester outperforms linear harvesters

Beeby, S. P., et. al. Smart Mater. Struct. **22**(7), 075022 (2013)

Summary

- In our analysis, at least 50% of signals would not be classified as single stationary frequency sources
- In these cases, we must deal with the narrowband operation of linear oscillator based harvesters
- Tunable options exist, and are probably mostly useful for cases where there is a single frequency that moves slowly in time, or for one time tuning based on manufacturing variation or temperature dependence
- Wideband nonlinear harvesters have been widely studied and are most useful for sources well modeled by white noise, or for sources with multiple dominant frequencies that can be captured under the bandwidth of the nonlinear harvester