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Overview of Challa, V. R., Prasad, M. G., Shi, Y., and Fisher, F. T.'s 2008 Paper on a Vibration Energy Harvesting Device with Bidirectional Resonance Frequency Tunability

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Introduction about Dr. M. G. Prasad

NOISE-CON 2020
JAZZIN' UP NOISE CONTROL
Must Go On (line)!
A Virtual Event

- ❑ Completed the Bachelor of Engineering at University College of Engineering, Bangalore, India
- ❑ Completed the M.S. of Science at Indian Institute of Technology, Madras, India
- ❑ Completed the Ph.D. research in the area of muffler acoustics through Herrick Laboratories, Purdue University in 1980.
- ❑ Since 1980, began faculty position at Stevens Institute of Technology in Hoboken, New Jersey where he has been teaching for nearly 40 years, guiding over 50 graduate students in both Masters and Ph.D. studies.
- ❑ “The privilege of a human is to wonder, ponder, practice and realize.”
  ---- from the website “Dr. M. G. Prasad: Memories and Moments”

Dr. M. G. Prasad (1950-2019)

Introduction

- The emergence of **low power and wireless devices** has sought portable and long lasting energy sources, especially for applications where the **replacement of batteries is unfeasible**.

⬇

- The **omnipresent vibration** energy allows harvesting energy on a continuous basis. However, for some other energy harvesting techniques, such as solar cells and thermoelectrics, are limited by the need for the presence of sunlight and thermal gradients.

⬇

- Until 2008, many designs of vibration harvesting systems are based on a **single resonance frequency**, which limits their performance in practical applications.

⬇

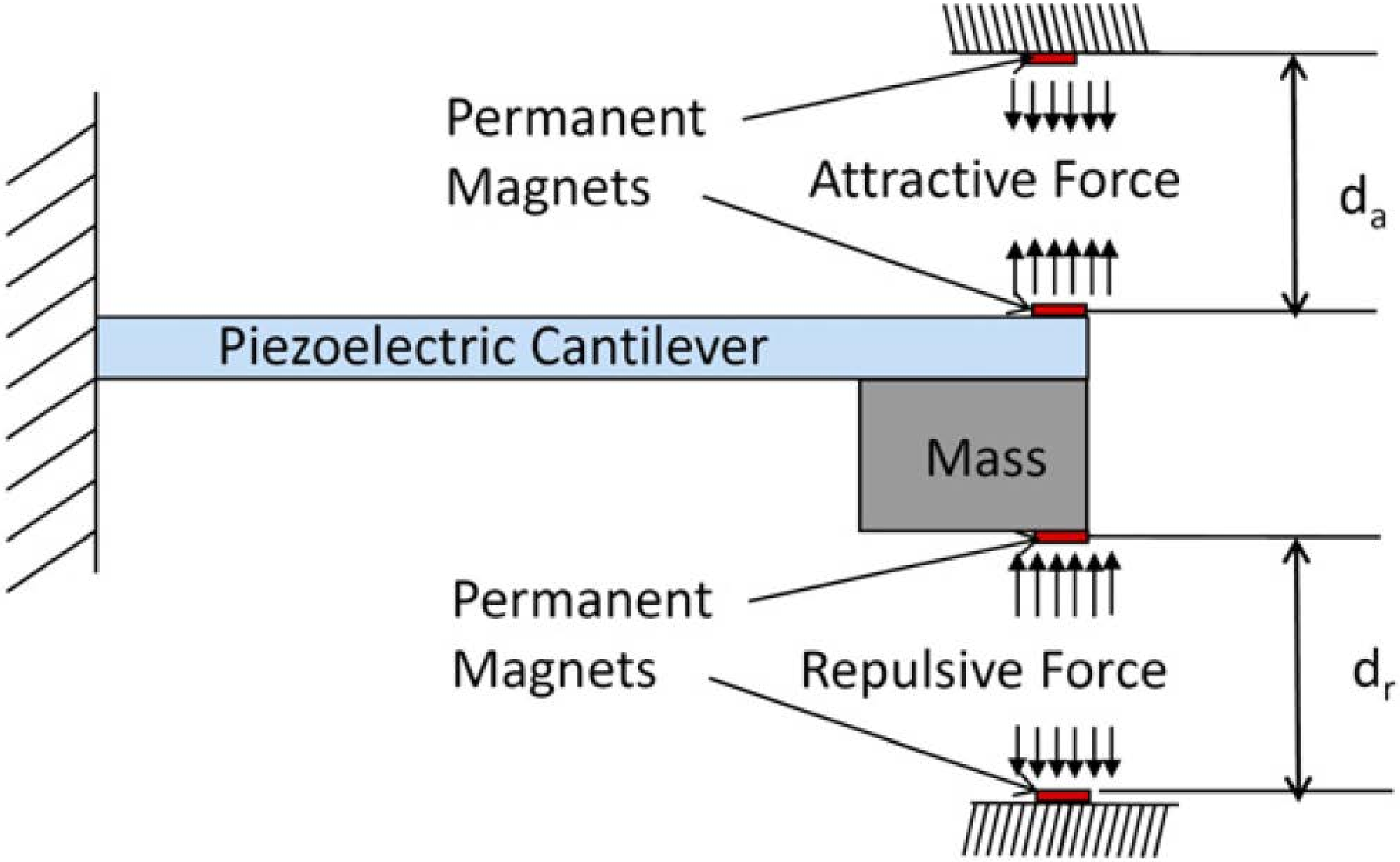
- A mechanism to **tune** the energy harvesting device is important

Previous Research about Tunable Energy Harvesting Devices

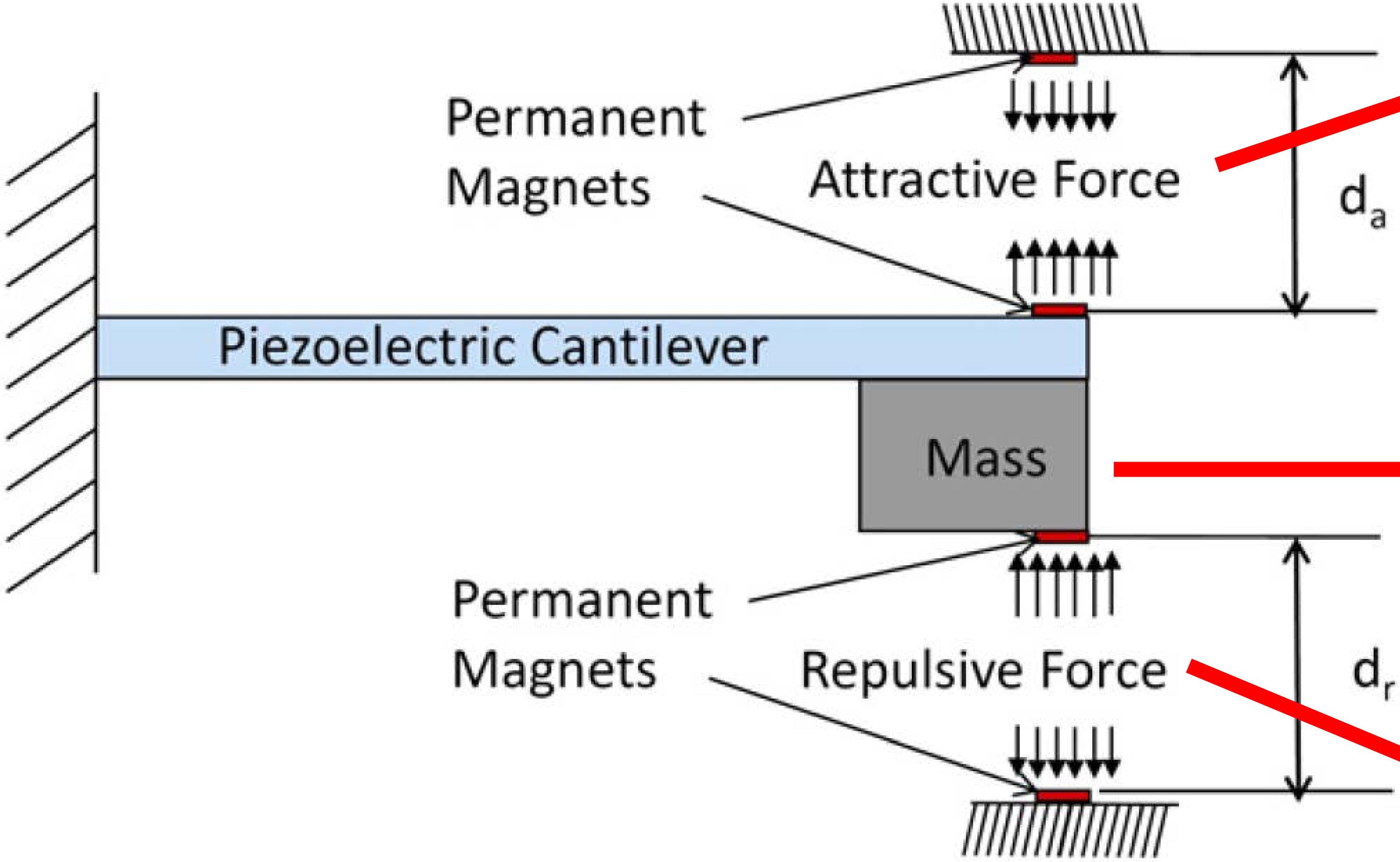
- ☐ In 2005, Roundy and Zhang proposed a tuning technique that applies an electrical input to a piezoelectric bimorph to alter the resonance frequency. But a **continuous input power** is required to maintain this change of resonance frequency which reduces the efficiency of energy harvesting device.
- ☐ In 2005, Malkin and Davis proposed a multi-frequency piezoelectric energy harvester consisting of a plurality of cantilevered beams from a fixed base. Although this gives the possibility of tuning over a large frequency range, a large set of the beams will not be in resonance and reduces the potential **power density** of such device.
- ☐ In 2006, Leland and Wright tuned the resonance frequency of the device by applying an axial compressive load to alter the stiffness of the simply supported beam.
- ☐ In 2006, Nishida included the development of a resonant energy micro-electromechanical system array to increase the power density of the energy harvesting device.

In summary, in terms of **power density** and **efficiency** over the **frequency range of operation**, improvement is still needed.

Schematic of Devices



Schematic of Devices



Introduce negative stiffness

A tip mass to lower the natural frequency, because ambient environmental sources are usually under 100 Hz

Introduce positive stiffness

Application of Magnetic Force

The magnetic force between two cylindrical magnets is:

$$F_{mag}(d) = \frac{B_r^2 A_m^2 (l+r)^2}{\pi \mu_0 l^2} \left(\frac{1}{d^2} + \frac{1}{(d+2l)^2} - \frac{2}{(d+l)^2}\right)$$

where,

d is the distance between the magnets

l is the length of the magnet

r is the radius of the magnet

B_r is the residual flux density of the magnets

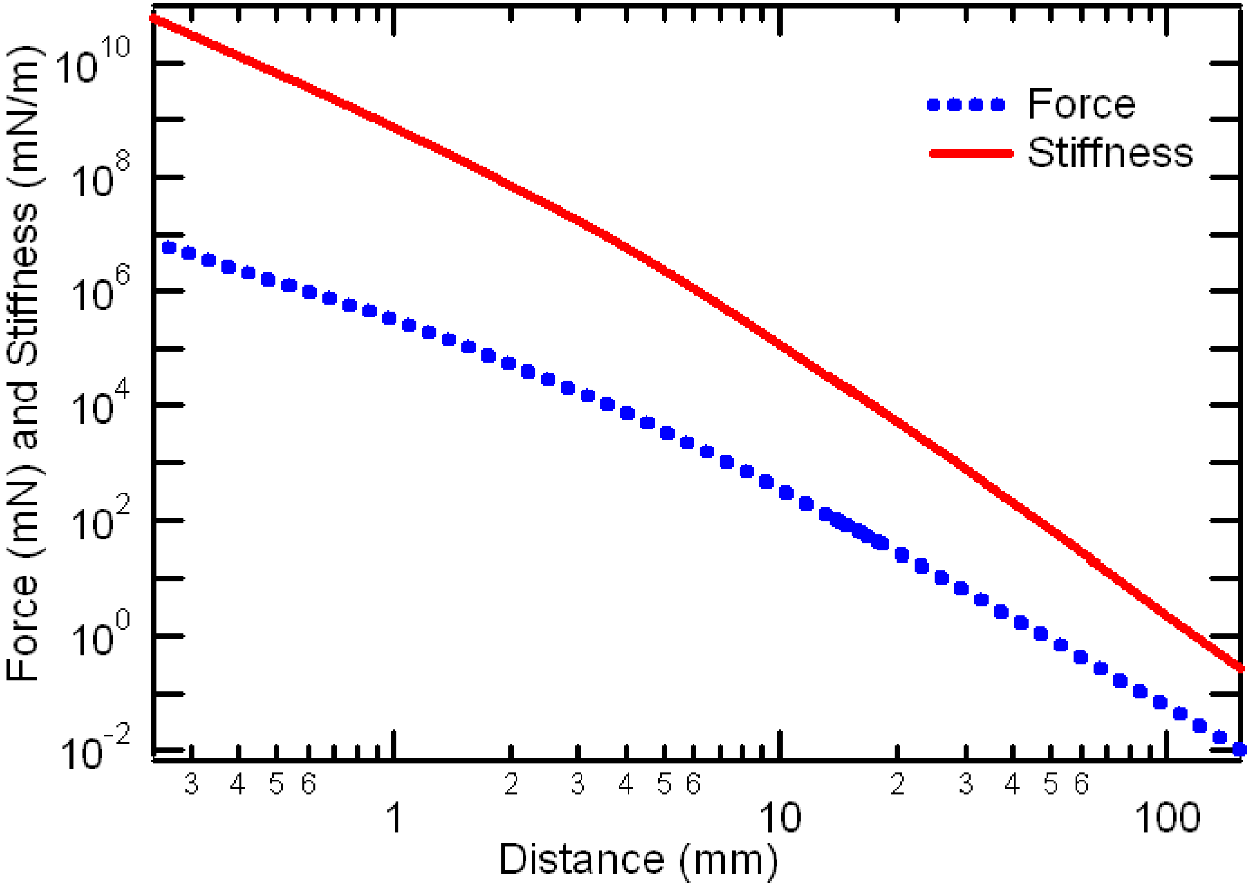
μ_0 is the permeability of the intervening medium

A_m is the common area between magnets

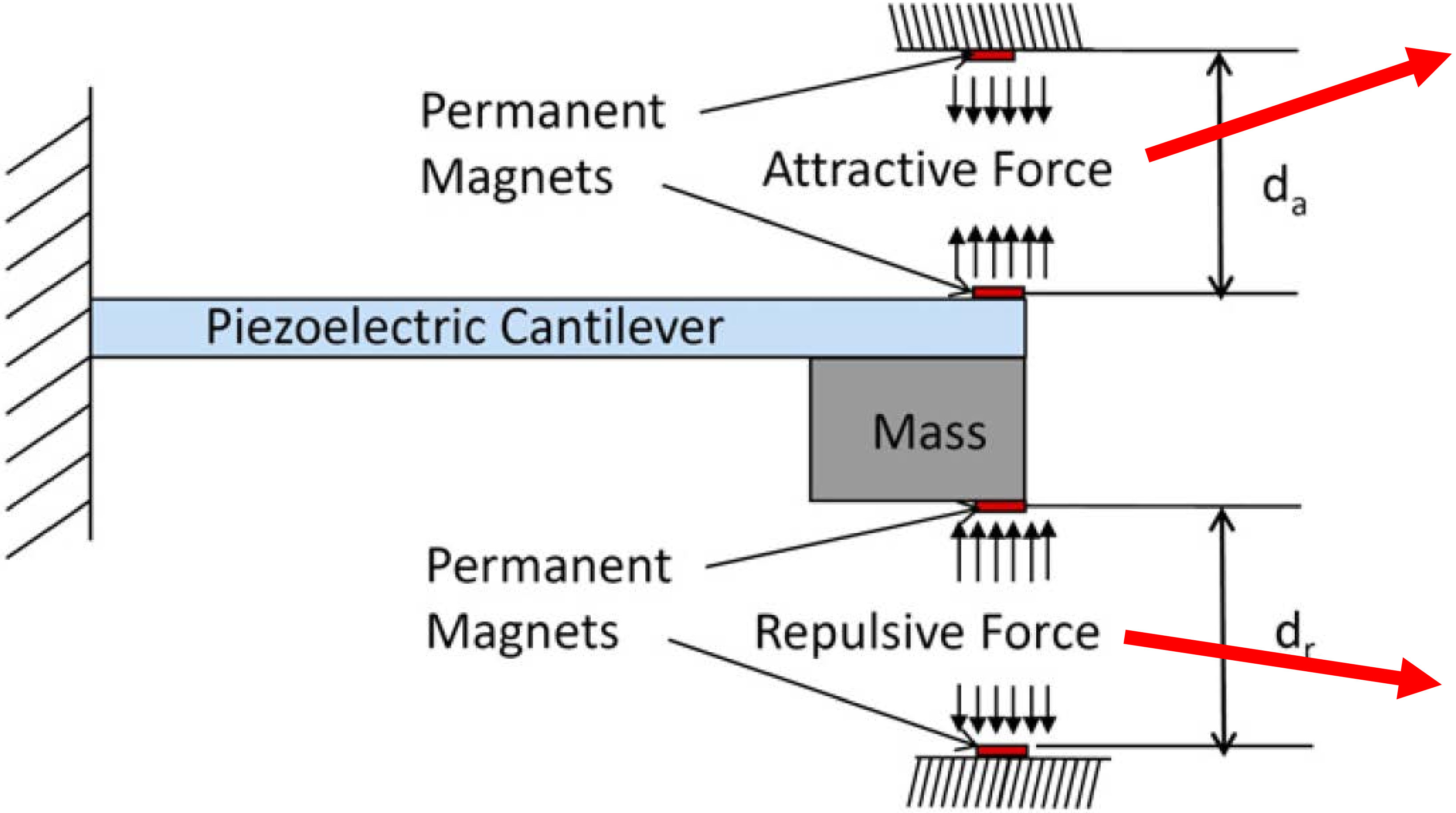
Note that the hysteresis between the magnetic force of attraction and repulsion is not considered

Application of Magnetic Force

Plot of the force and stiffness versus separation distance between two cylindrical magnets in log-log scale



Limitations of the Application of Magnetic Forces



When d_a is small enough,

F_{mag} will be larger than the stiffness force of the beam.

Then the two magnets will snap together and changes the overall boundary condition

When F_{mag} is too large, the stress induced will exceed the yield strength of the beam.

Effect of Magnetic Force on Resonance Frequency

When no magnetic force exist, the stiffness and mass of a multilayered cantilevered beam is:

$$K_{beam} = \frac{b}{4L^2}\left(\sum_{i=1}^{n_1} n_i E_i h_i^3 + \sum_{j=1}^{n_2} n_j E_j h_j^3\right)$$

$$m_{eff} = m_t + 0.23bL\left(\sum_{i=1}^{n_1} n_i \rho_i h_i + \sum_{j=1}^{n_2} n_j \rho_j h_j\right)$$

where,

b is the width of the beam

n_1, n_2 is the number of piezoelectric and electrode layers respectively

E_i, E_j is the Young's modulus of piezoelectric and electrode layers respectively

h_i, h_j is the heights of each piezoelectric and electrode layer respectively

ρ_i, ρ_j is the densities of piezoelectric and electrode layers respectively

L is the length of the beam

m_t is the tip mass

So the natural frequency is:

$$\omega_{beam} = \sqrt{\frac{K_{beam}}{m_{eff}}}$$

Effect of Magnetic Force on Resonance Frequency

The magnitude of the magnetic force induced stiffness $K_{mag} = \pm\bar{K}_{mag}$ is:

$$\bar{K}_{mag}(d) = \left|\frac{\delta F_{mag}}{\delta d}\right| = \left|\frac{B_r^2 A_m^2 (l+r)^2}{\pi \mu_0 l^2}\left(-\frac{2}{d^3} - \frac{2}{(d+2l)^3} + \frac{4}{(d+l)^3}\right)\right|$$

where the sign is positive for repulsive mode and negative for attractive mode.

Then the total effective stiffness is: $K_{eff} = K_{beam} + K_{mag}$

Thus, if the desired resonance frequency is ω_t, then the required K_{mag} is:

$$K_{mag} = m_{eff}(\omega_t^2 - \omega_{beam}^2)$$

Power Output Modeling of the Cantilevered Beam

The output power is given as:

$$P = \frac{V^2 R_L}{(R_s + R_L)^2}$$

where

the R_L is the load resistance,

the R_s is the impedance of the piezoelectric cantilever beam (acts as a capacitor C_p):

$$R_s = \frac{1}{\omega_t C_p} \qquad C_p = \frac{n\, \epsilon\, W\, L_e}{t_p}$$

the V is produced voltage:

$$\mathrm{V} = \frac{-d_{31} t_p \sigma_{beam}}{\epsilon}$$

where,

n is the number of piezoelectric layers

W is the width of the piezoelectric layers

L_e is the length of the electrode

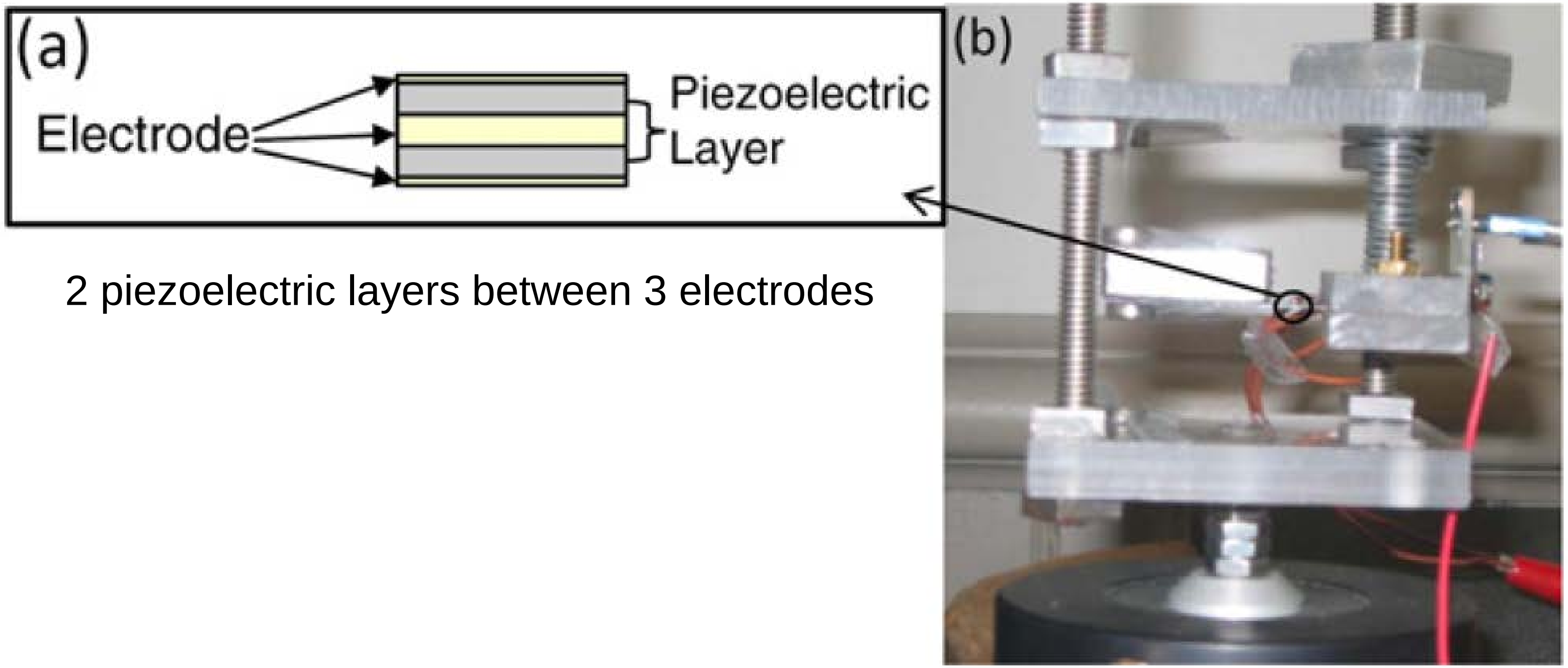
t_p is the thickness of the piezoelectric layer

d_{31} is the piezoelectric strain constant

ϵ is the dielectric constant of the piezoelectric material

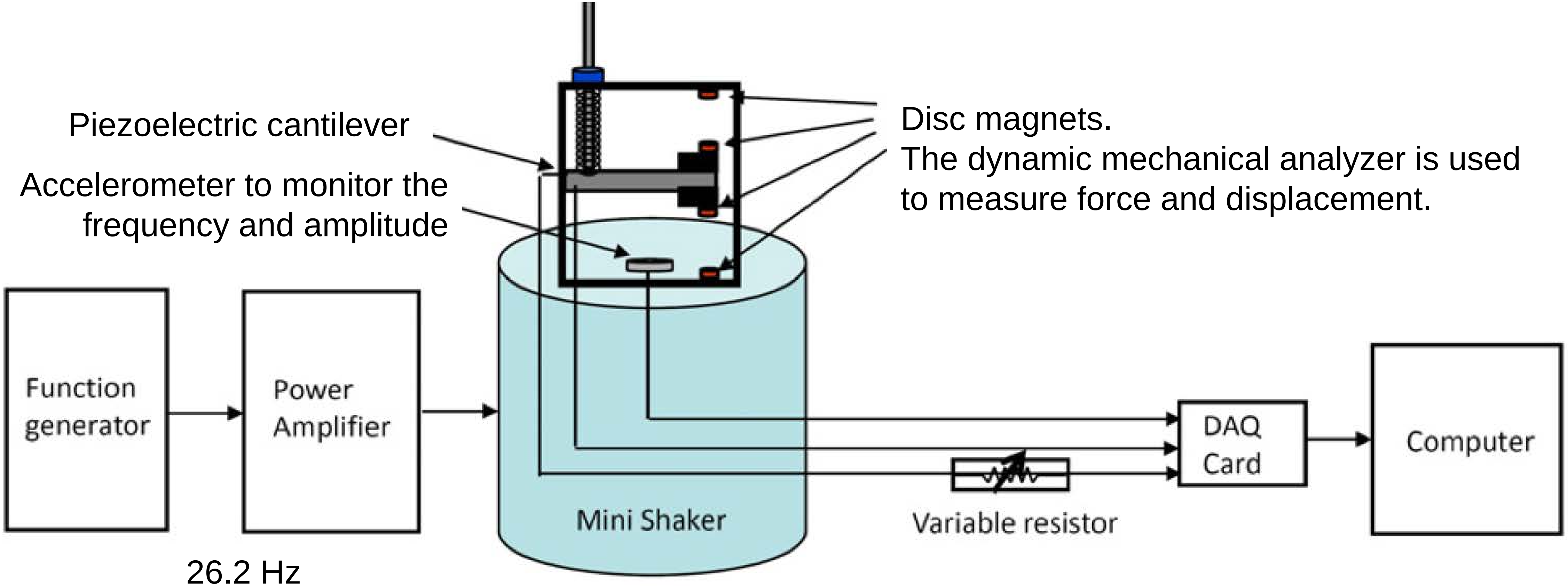
σ_{beam} is the average effective stress per unit length

Experimental Setup



2 piezoelectric layers between 3 electrodes

Experimental Setup



Screw-spring mechanism to change the distance between to the magnets

Piezoelectric cantilever

Accelerometer to monitor the frequency and amplitude

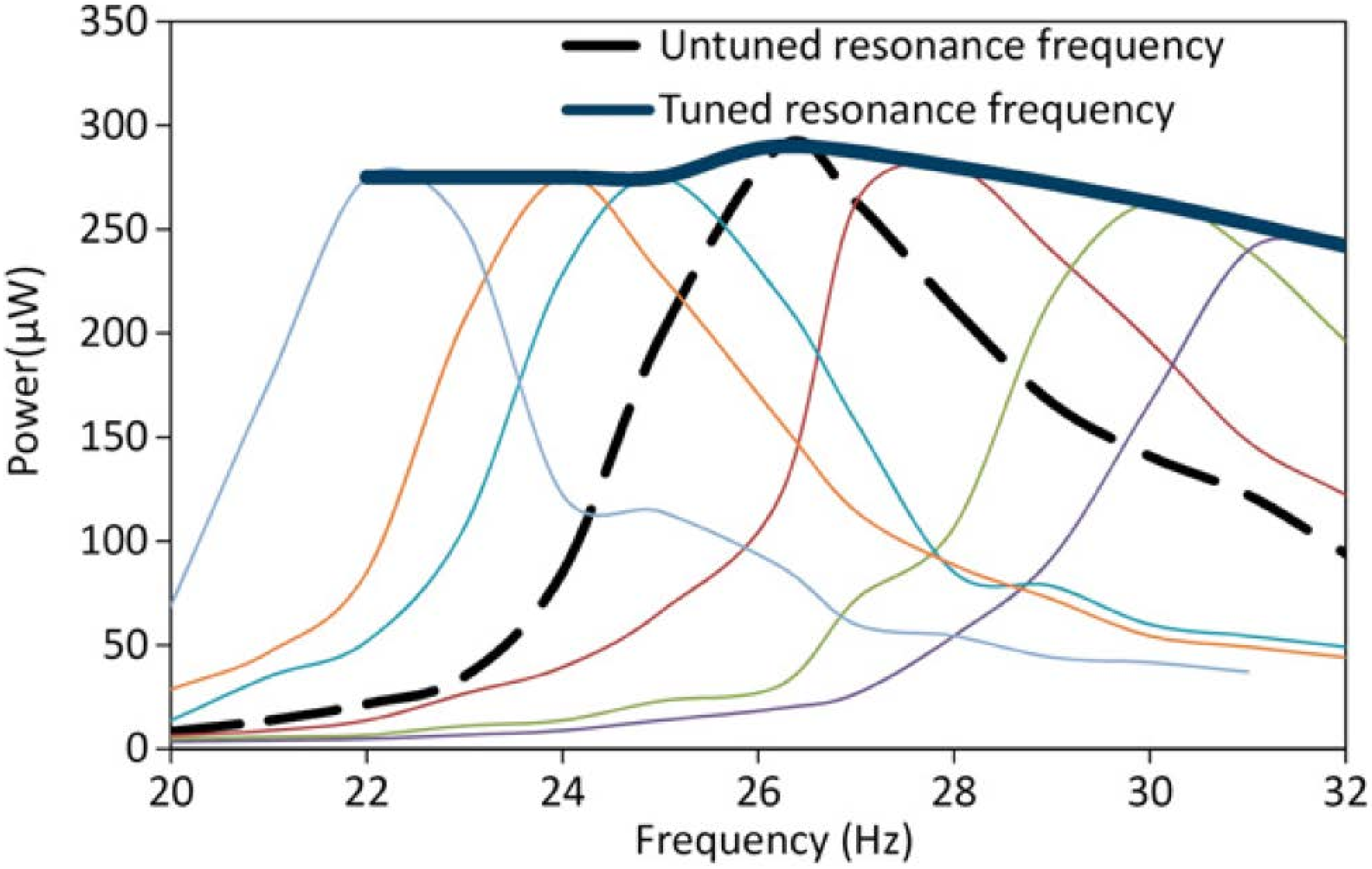
Disc magnets.

The dynamic mechanical analyzer is used to measure force and displacement.

26.2 Hz
(alter between 20 and 32 Hz)
0.8 $m\ s^{-2}$

Experimental Results

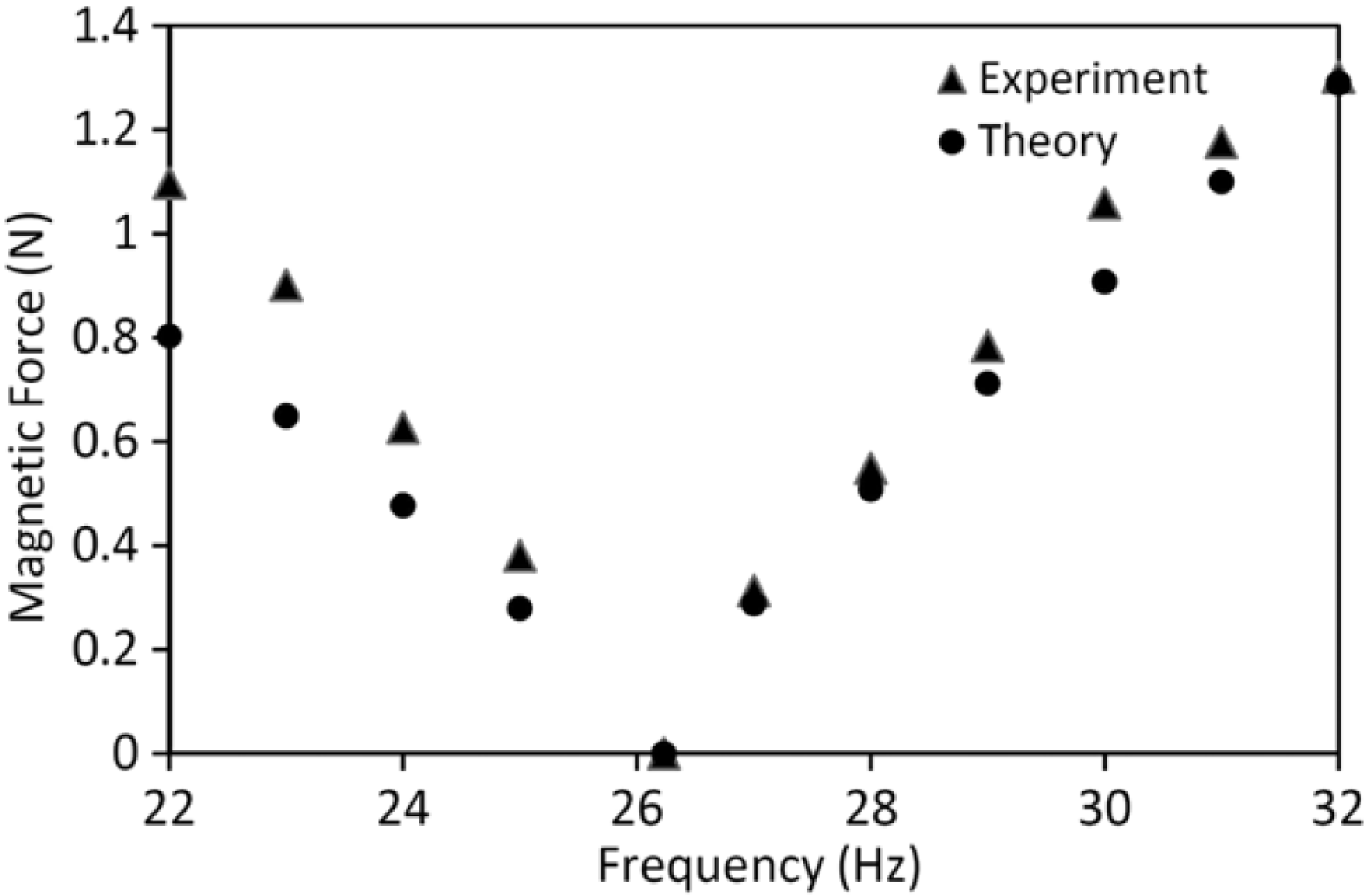
Experimental values of power output versus resonance frequency



The tuned energy harvesting system works well.
(Note that below 22 Hz, the magnets come into contact in attraction mode)

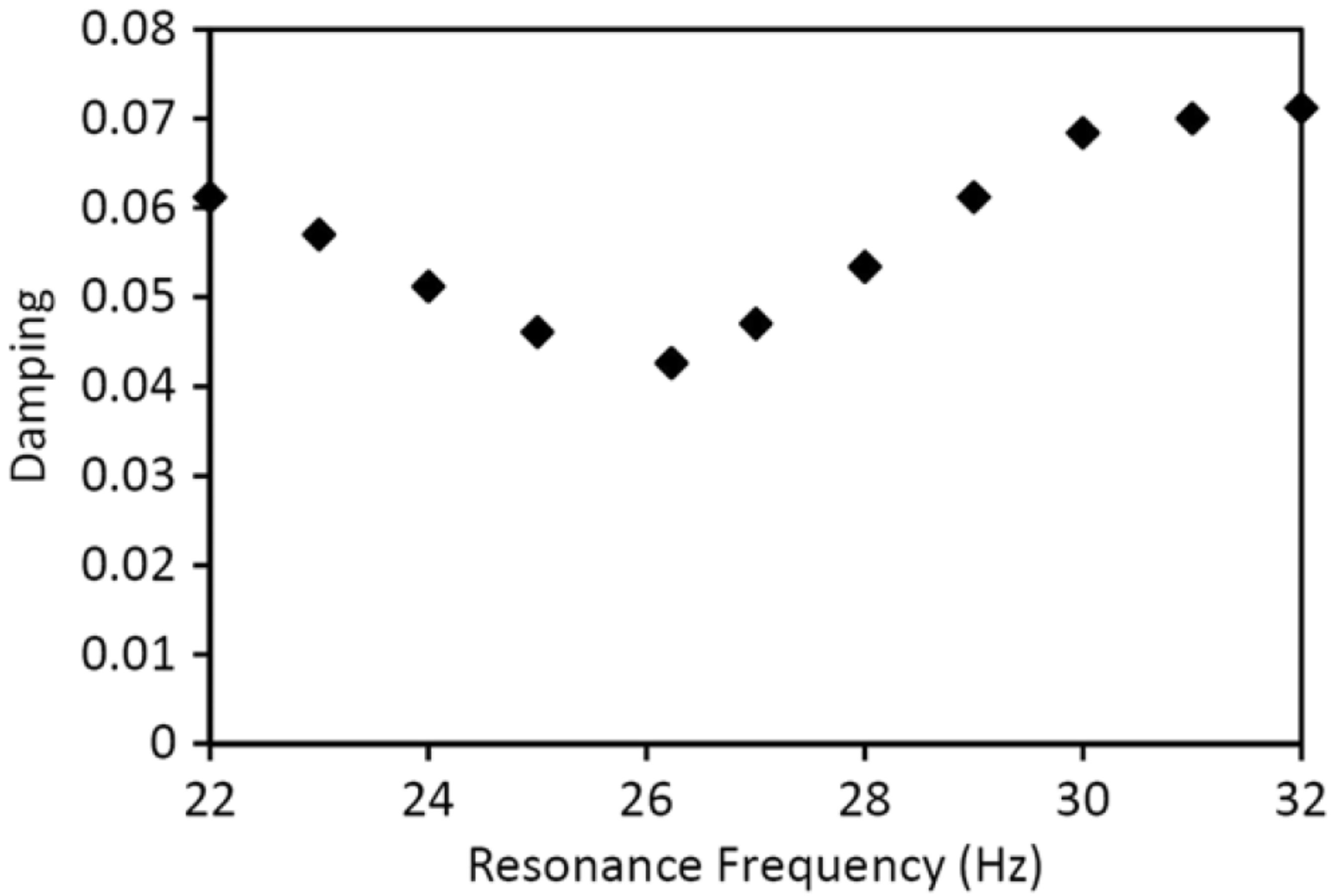
Experimental Results

Experimental and theoretical values of applied magnetic force versus resonance frequency



Experimental Results

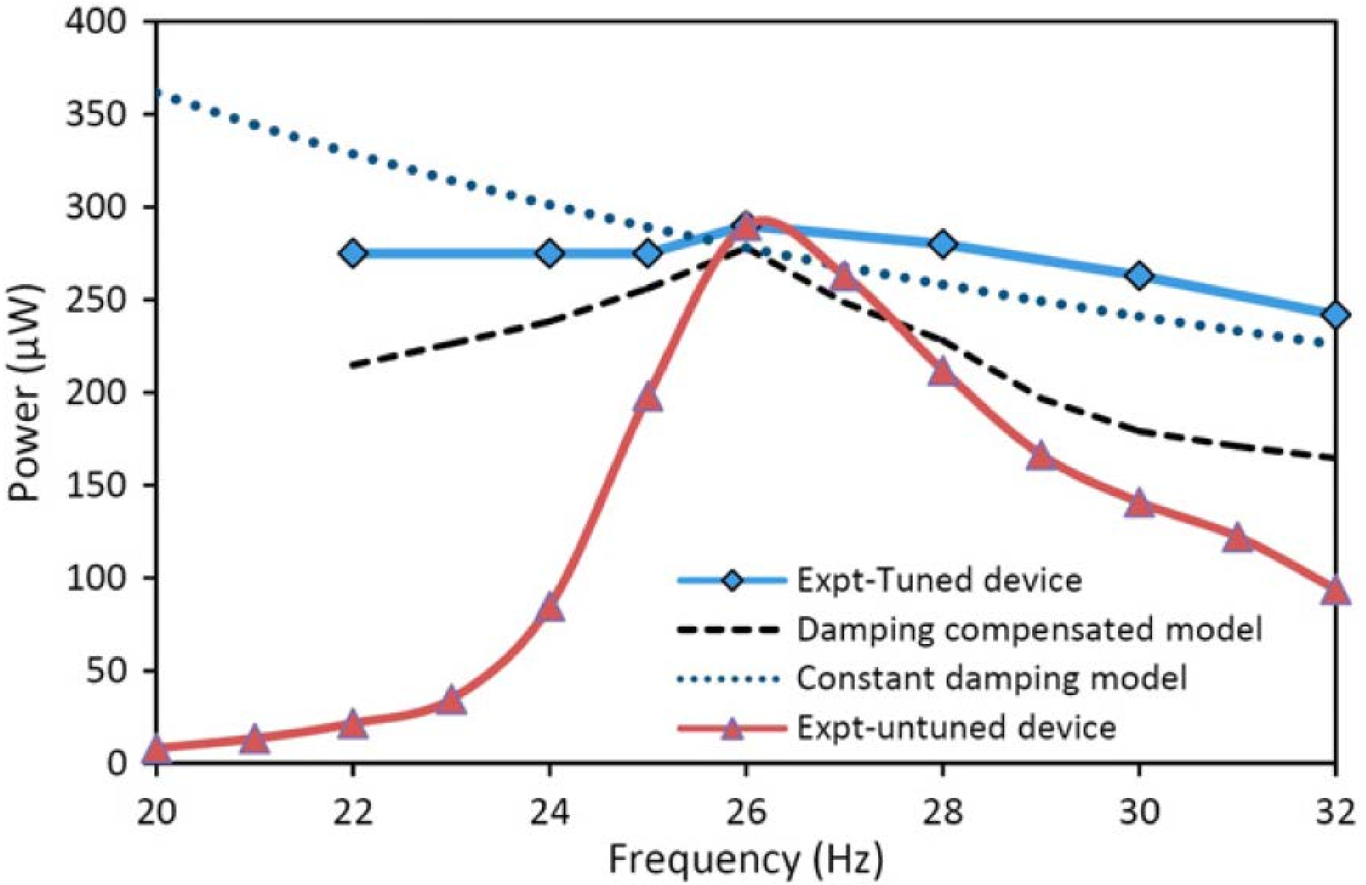
Experimentally measured values of damping versus resonance frequency



The damping of the piezoelectric beam increases with the increase of applied magnetic force

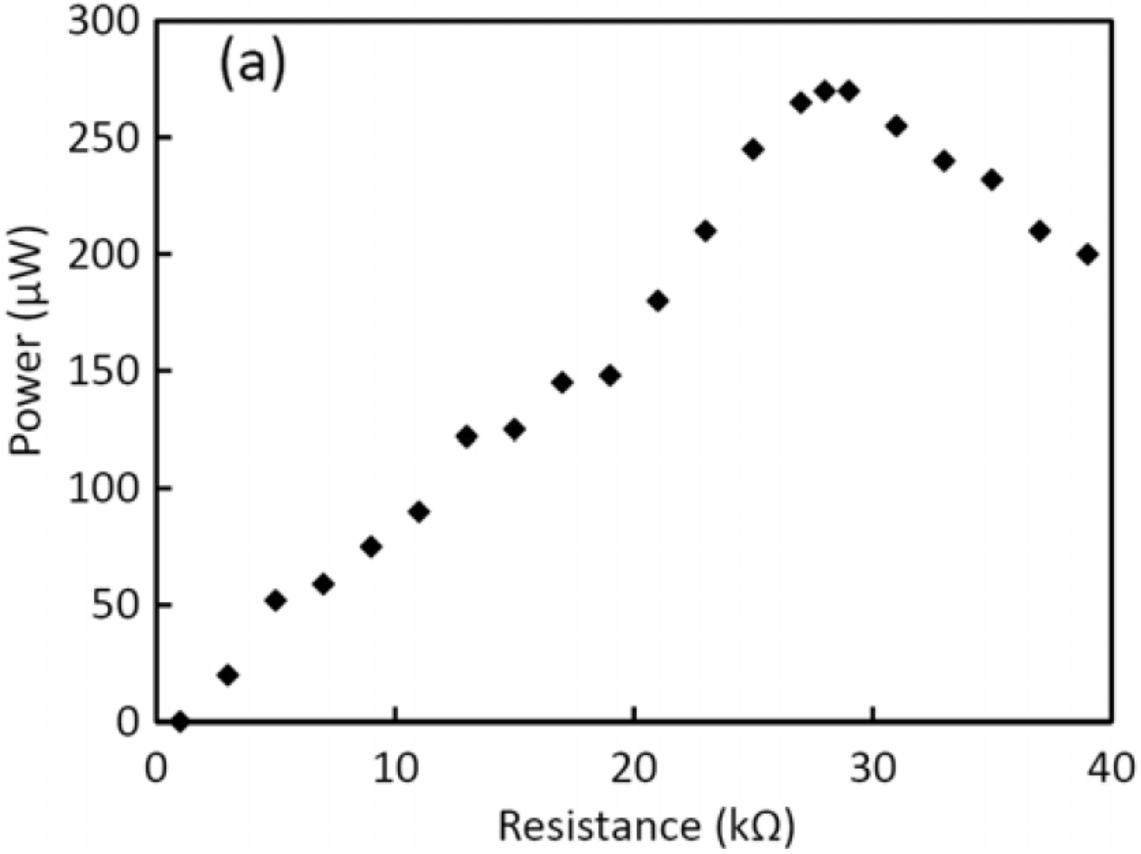
Experimental Results

Comparison of experimentally measured power output with theoretical predictions using the constant damping and damping compensated models

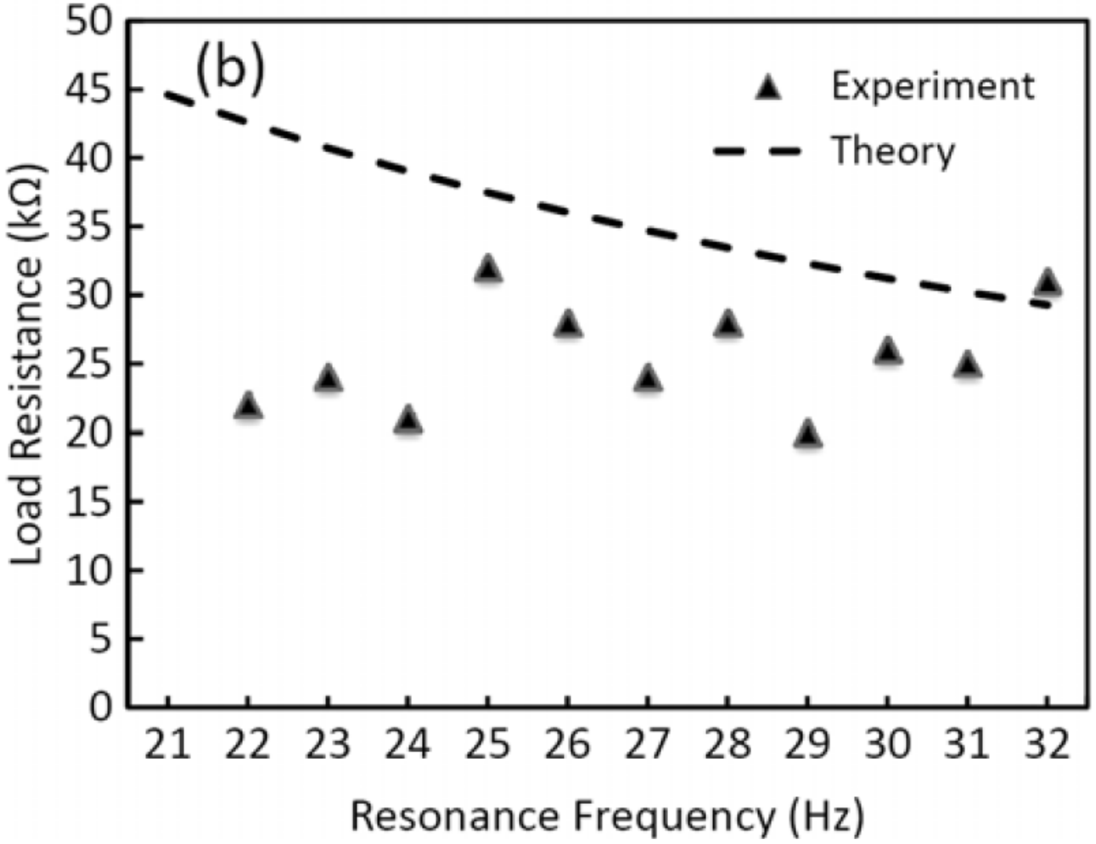


Experimental Results

(a) Power versus load resistance at 26.2 Hz



(b) Optimal load resistance versus resonance frequency



The discrepancy between theoretical and experimental value is because the change of load resistance changes the damping of the system which alters the mini-shaker

Summary

- The proposed approach can successfully tune the resonance frequency of the power harvesting system.

- The resonance frequency is bidirectionally tunable (about $\pm 20\%$).

- The proposed prototype has high bandwidth and high power density.

- This approach is semi-active, which is more efficient than active method.

- The drawback of this approach is that: the use of magnetic force will introduce additional damping to the power harvesting system which reduce the output power.

Some Work After this Paper

- In 2009, the author further investigated the damping induced by this approach such that the damping can be matched for a higher power output.
- In 2009, Reissman et al. combined this approach with another method to achieve a simpler design.
- In 2010, Zhu et al. proposed a new design such that the tuning mechanism has little effect on the total damping.
- In 2011, the authors proposed an improvement of this approach to achieve autonomously tuning the resonance frequency.
- In 2012, Tang et al. demonstrated that the nonlinearities introduced by magnets are beneficial in transition region compared with linear configuration. And the repulsive configuration of magnets is preferable for ultra-low-frequency vibration.

…….

Nowadays, more and more work were done in the vibration energy harvesting system using magnetic force.

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