On the Energy Transfer Performance of Mechanical Nanoresonators Coupled with Electromagnetic Fields: Applications with Magnetic Nanoparticles

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Wireless Delivery of Energy at Nano scale

• Wireless? Hmm.. Contact-less.

• Applications
  • Remote targeted biological actuation
  • Nanomedicine
  • Nanorobotics

• Building block for nanoscale communication systems (Networks)
  • *Biologically-Enabled* wireless networks
• We are looking for an efficient “Energy Channel” to send a message (meaningful and timely bundles of energy) to a nanodevice.
  • No physical contact
  • *Localized* and *Selective* interaction

• **Electromagnetic coupling**
  • Static vs. High Frequency?
  • Magnetic vs. Electric?

• **EM coupled Mechanical Nanoresonators** to transduce EM energy via mechanical vibrations.

• **Resonance!**
• We consider a “purely classical” model for electromagnetic coupling of mechanical nanoresonators.

• We are interested in quantitative assessment of the energy transfer at resonance.

• We compare the performance of magnetic coupling with electric coupling.
Methodology

• Resonant scattering theory (Coupled-mode theory)
  • Fluxes instead of Forces.
• We consider the biological safe temperatures (RT)
• We assume that low viscosity conditions is synthetically achievable in the engineered system.
Mechanical Model

- Cantilever Beam
- Specialized Tip (Coupling)

Resonant Energy Transfer

- Scattering Theory
- Cross Section
- Energy Deposit

The system's natural resonant energy transfer performance is achieved by applying the theory of scattering in electromagnetic waves. The steady state solution of the system is obtained from Eq. 3. By definition, the width of the cross section given by the resonant system equals to $\omega_0 = \sqrt{\frac{k}{m_f}}$. The quality factor is $Q = \frac{\sqrt{k m_f}}{D}$.

The maximal energy transfer occurs at the resonant frequency and can be written as

$$\Delta U_r = \frac{48 \Phi c^2}{\omega_r^2} \left( \frac{\Gamma_s}{\Gamma_a} \right) = \frac{48 \Phi c^2}{\omega_r^4} \Gamma_s Q_a^2.$$
The stochastic term from Eq. 1. The system's natural frequency can be determined from the coupling type. With a similar viscoelastic model, the scattering process is given by

\[
E_{scattering} = \frac{1}{2} k x^2_m, \quad \text{for} \quad k \neq 0
\]

\[
\Gamma_s = \frac{q^2}{4\pi\epsilon_0} \frac{2\omega^4}{3c^3 k}, \quad \text{for} \quad k \neq 0
\]

\[
\Delta U_r = \frac{q^2}{4\pi\epsilon_0} \frac{32\Phi Q_a^2}{ck}
\]

\[
\mu/Lc \approx q.
\]

to achieve the same performance
• We performed our analysis on few nanoresonators that are already demonstrated in the literature:

• Example: **Nanotube Radio**
  K. Jensen, J. Weldon, H. Garcia, and A. Zettl, UC berkeley, 2007

• NR uses *electric* coupling

• We show that the same energy transfer performance is reached by replacing the electric dipole of the original nanotube prototype with a spherical Magnetite Nanoparticle of radius 160 nm.
• Natural Example: *Magnetosomes*

• We show that a significant amount of energy ($\sim 10^4 \text{kT}$) can be deposited on magnetically coupled magnetosomes at resonance. This requires a synthetic encapsulation of the magnetic particle to reduce the viscosity.
Ongoing and Future Work

- Non-linear models
- Verification of the results by numerical methods such as Finite-element simulations
- Explore realistic mechanisms to demodulate the information from incoming energy bundles (messages).
- Manufacturing of a nano-receiver
Summary

• magnetically coupled mechanical nanoresonators are promising tools to deliver energy at nanoscale.

• The energy transfer performance of magnetically coupled systems is as good as their electrically coupled counterparts, if not better, within the scale of interest.

• Several applications exist in cellular biology (remote control and actuation), nanomedicine, nanorobotics.
An example of existing models for Biological Actuations

\[ B = B_{\text{ext}} \cos(\omega t) \]

Magnetic field

Magnetic Particle (micro ~ nano)

Mechanosensitive ion channel