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One and Two-Degrees-of-Freedom Gravitational Energy Harvesters for Ultra-Low-Power IoT

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Abstract:

- **Gravitational energy harvesters** (GEH) convert the motion of an **asymmetric magnetic spring** excited by external vibrations into **induced electromotive force** on pick-up coils.
- The **non-linear** dynamic characteristics of **softening stiffness** and **electromagnetic damping** are modeled and experimentally validated.
- One and two-degrees-of-freedom configurations are compared in terms of **power Frequency Response Functions**.
- An **autonomous Wireless Sensor Node GEH-powered** for **freight trains** monitoring is presented with **ideally infinite lifespan**.
- Future works will regard experimental tests of GEH-WSN on a freight train during working conditions.

One-degree-of-freedom Gravitational Energy Harvester

Equation of motion: mass-spring-damper

$$m\ddot{z} + c(z)\dot{z} + k(z)\,z = mY_0\sin(\Omega t)$$

Non-linear characteristics numerical models:

- "Softening" magnetic spring stiffness
- Electromagnetic damping due to parasitic currents in coils

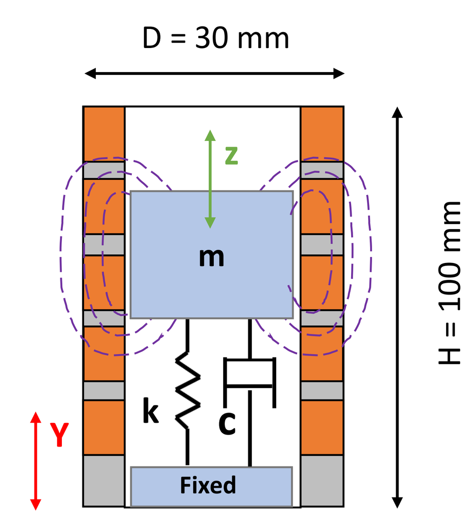

Figure 1– 1DOF GEH scheme

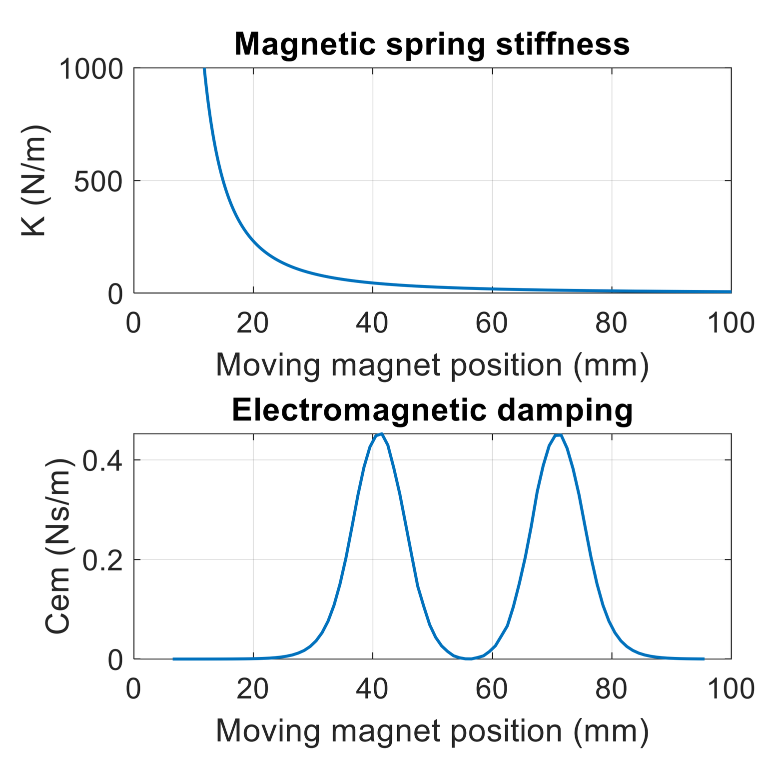

Figure 2– 1DOF non-linear characteristics

Optimization design process:

- Moving and fixed magnets volume ratio influence resonance frequency and equilibrium position of magnetic spring.
- Coil length, number of turns, cross-section diameter and position along the tube influence output power and electromagnetic damping.

Experimental FRFs:

- Non-linearities shift resonance frequencies to lower values with higher excitation amplitudes.
- **Max. RMS Power = 32 mW @ 4 Hz 0.5 g**
- **NPD = 2.61 mW cm^{-3} g^{-2}**

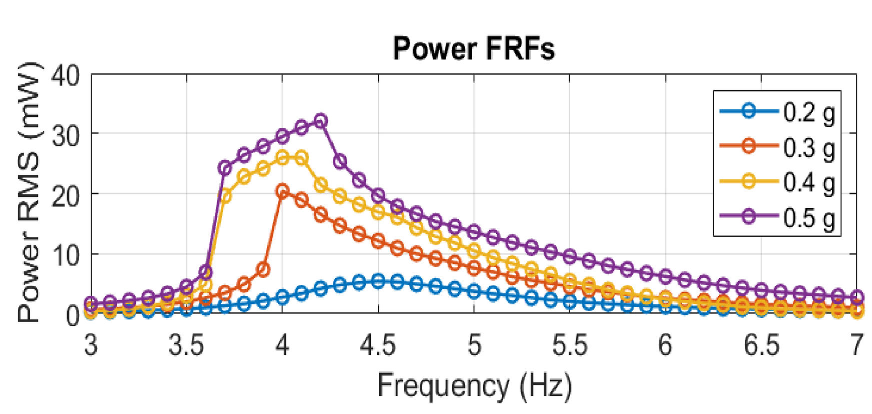

Figure 3– 1DOF Power FRFs

Two-degrees-of-freedom Gravitational Energy Harvester

Equations of motion: series of two mass-spring-damper

$$\begin{cases} m_1\ddot{z_1} + c_1(z_1)\dot{z_1} - c_2(z_2)\dot{z_2} + k_1(z_1)z_1 - k_2(z_2)z_2 \\ \qquad = m_1 Y_0 \sin(\Omega t) \\ m_2(\ddot{z_1} + \ddot{z_2}) + c_2(z_2)\dot{z_2} + k_2(z_2)z_2 = m_2 Y_0 \sin(\Omega t) \end{cases}$$

Non-linear characteristics numerical models:

- Series of two "softening" magnetic stiffness
- Electromagnetic damping due to parasitic currents in series-connection of two coils

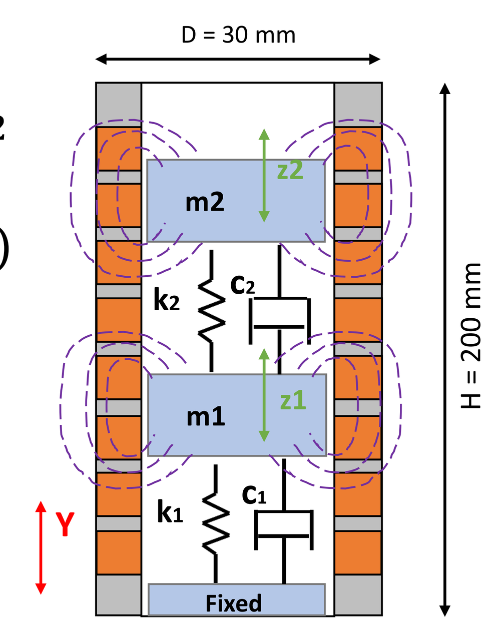

Figure 4– 2DOF GEH scheme

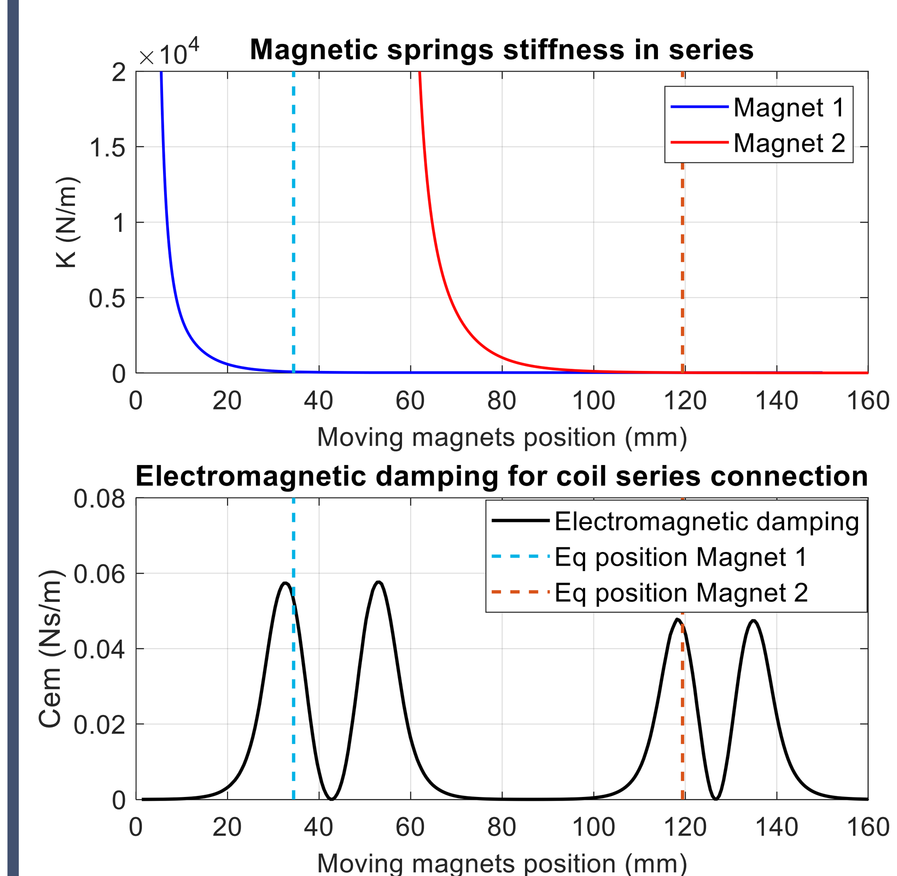

Figure 5– 2DOF non-linear characteristics

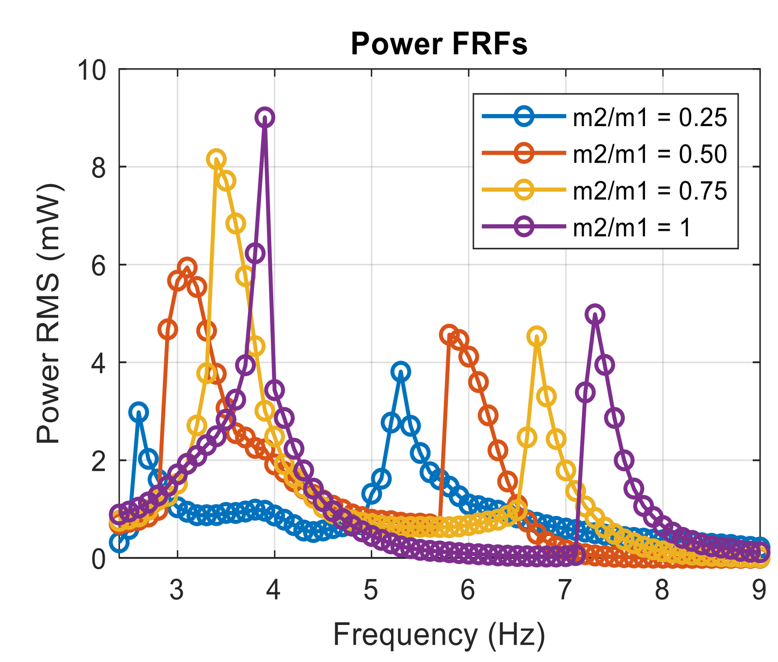

Figure 6– 2DOF Power FRFs

Experimental FRFs:

- Two resonance peaks depending on mass ratio of moving magnets.
- Flexibility of tuning peaks to two fundamental excitation frequencies.
- **Max. RMS Power = 8 mW @ 3.4 Hz 0.4 g, 5 mW @ 7.5 Hz 0.4 g**
- **NPD = 0.23 mW cm^{-3} g^{-2}** lower due to double tube height

Autonomous GEH-powered Wireless Sensor Node for Freight Train temperature monitoring

- Power management circuit achieves **power efficiency of 65%** from GEH to battery.
- Li-Po rechargeable battery to guarantee continuative monitoring when train stops.
- Ultra-low-power WSN consumes 3.3V 20mA during RX-TX, 0.1 mA during sleep phase.
- Input power charging the battery goes from 2.5 mW at 0.2 g, up to 15 mW at 0.5 g in resonance conditions.
- With a duty cycle of one connection every one second of sleep or more**, the input charging power exceeds the consumption** already **at low excitation of 0.2g in resonance conditions.**
- Effective input charge under real train vibrations spectrum must be evaluated.

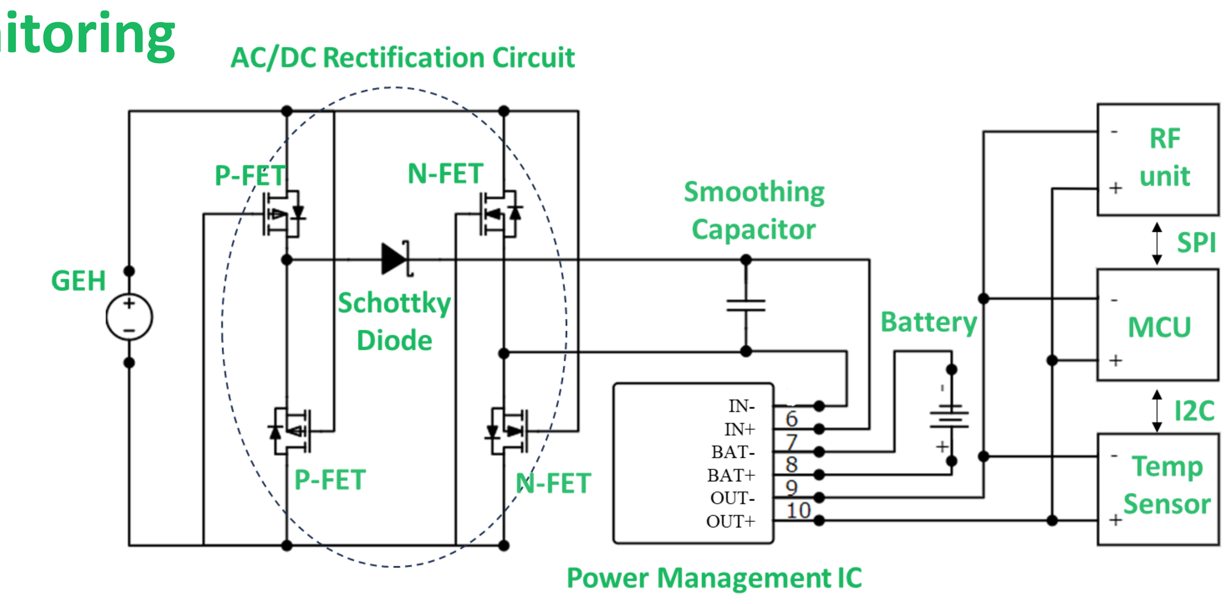

Figure 7– GEH-WSN circuit scheme