Motion Energy Harvesters: Mechanisms and Fundamental Limits

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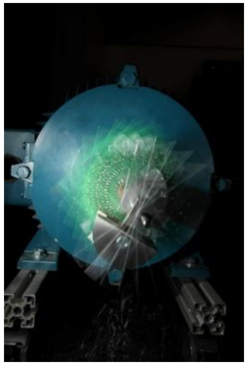

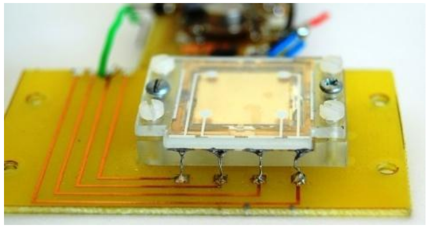

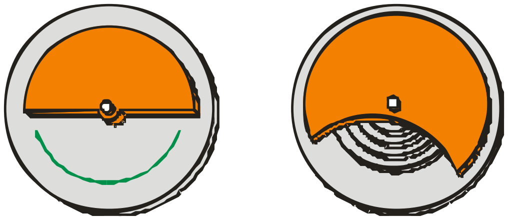

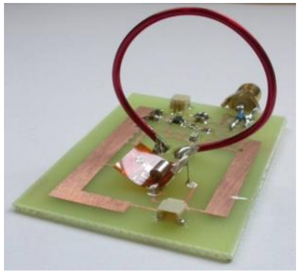

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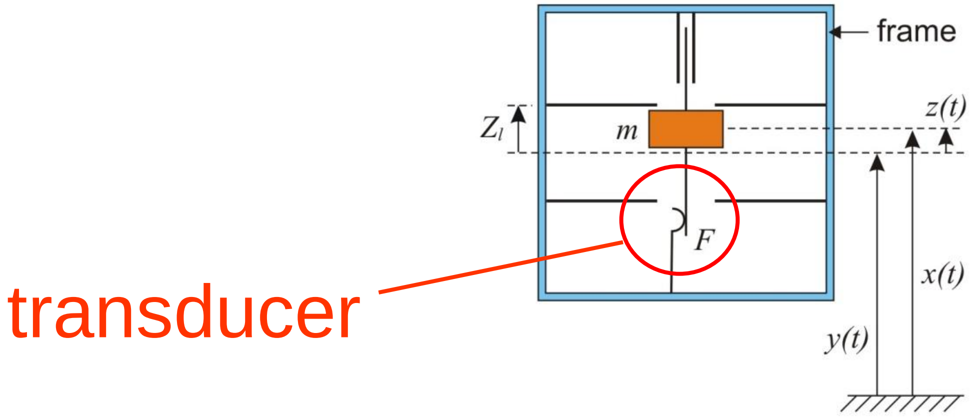
Inertial Harvesters

- Mass mounted on a spring within a frame
- Frame attached to moving “host” (person, machine…)
- Host motion vibrates internal mass
- Internal transducer extracts power



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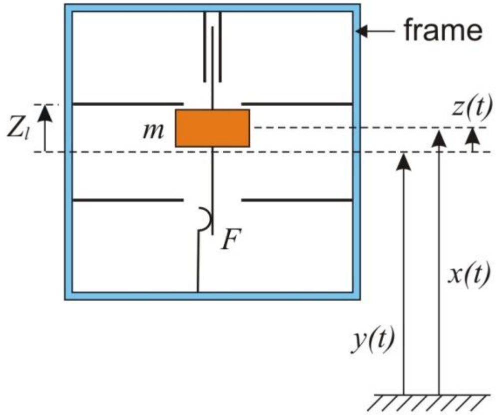
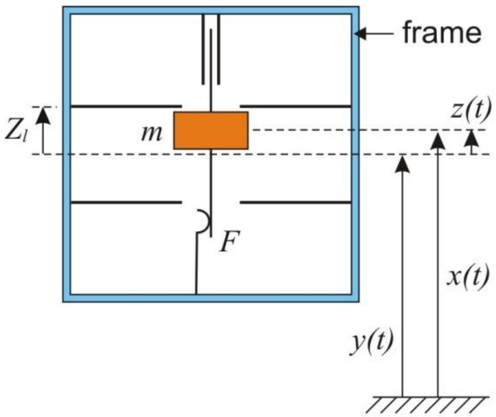
Available Power from Inertial Harvesters

assume:

- source motion amplitude Y_o and frequency ω
- Proof mass m, max internal displacement z_o



- Peak force on proof mass $F = ma = m\omega^2 Y_o$
- Damper force < F or no movement
- Maximum work per transit $W = Fz_o = m\omega^2 Y_o z_o$
- Maximum power $P = 2W/T \;\; = m\omega^3 Y_o z_o/\pi$



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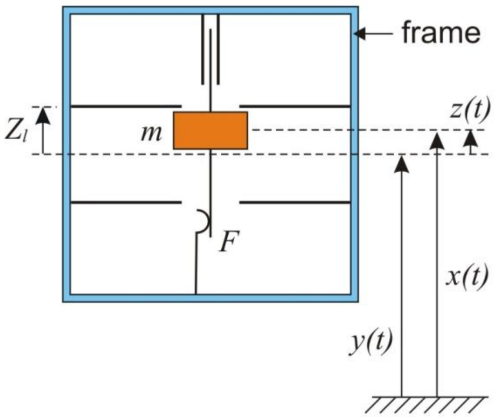
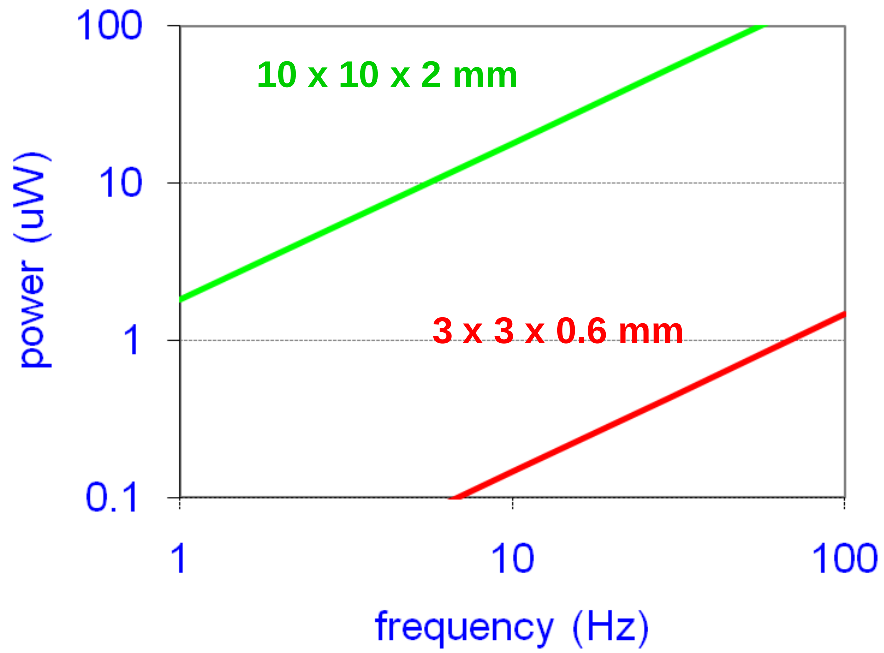
Implications for Scaling

- Maximum power $P = m\omega^3 Y_o z_o/\pi$
- For length dimension L, m scales as L^3
- Z_o scales as L
- So power scales as L^4
- Power density falls as size reduces



How much power is this?



Plot assumes:

- Si proof mass (higher densities possible)
- max source acceleration 1g (determines Y_o for any f)

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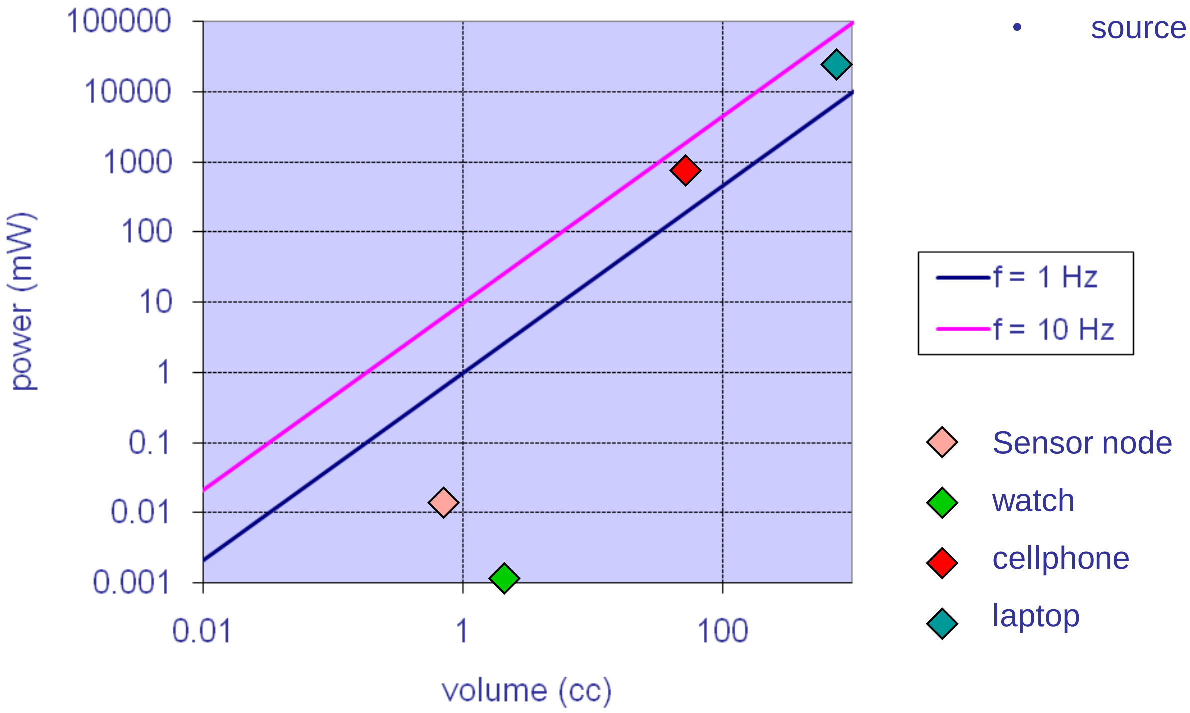
Achievable Power Relative to Applications



Plot assumes:

- proof mass 10 g/cc
- source acceleration 1g

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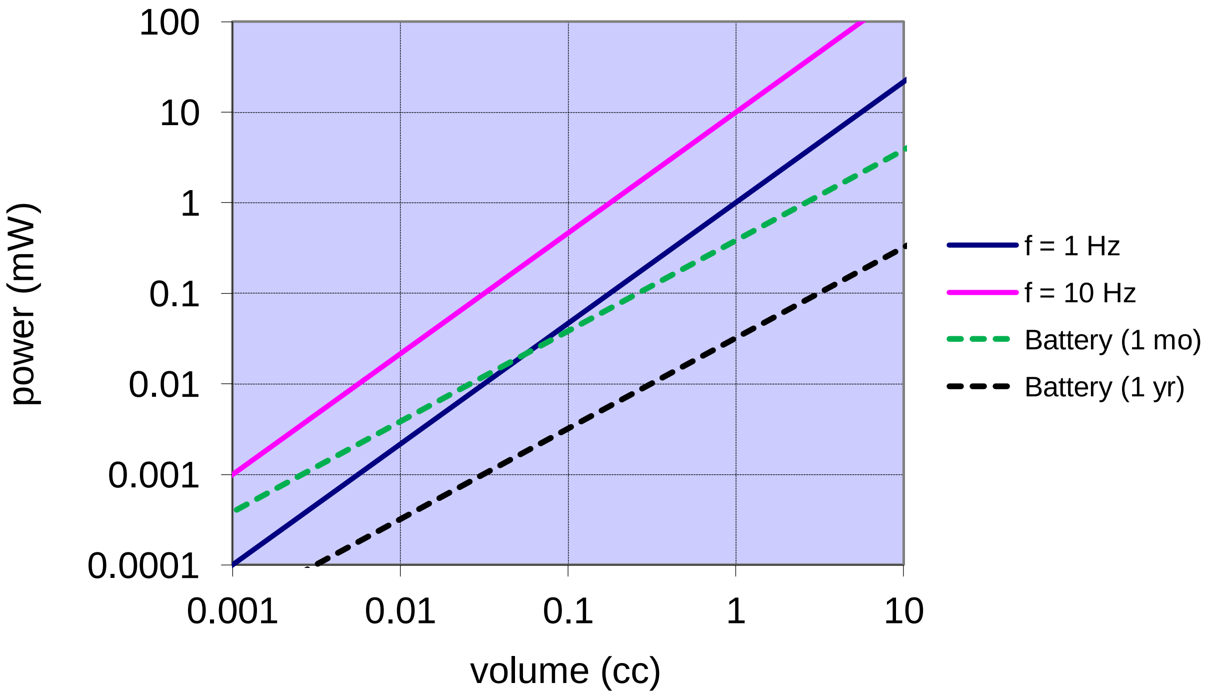
Possible Power Relative to Batteries



Plot assumes:

- proof mass 10 g/cc
- source acceleration 1g

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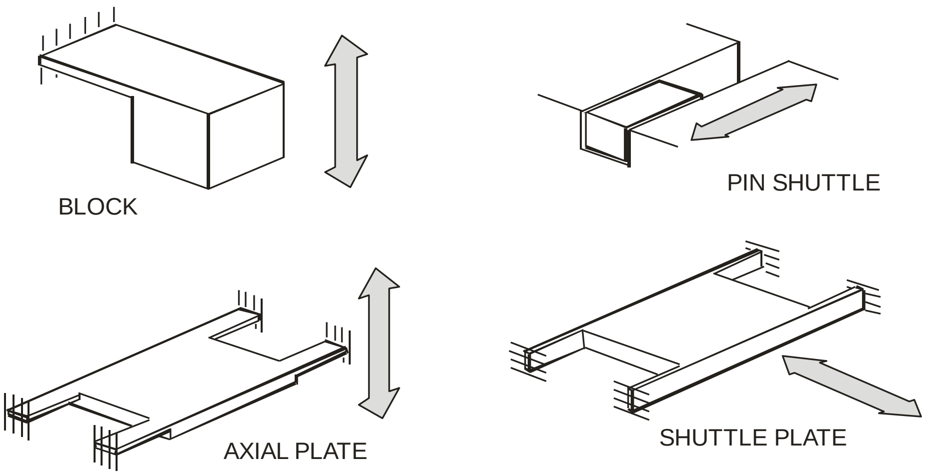
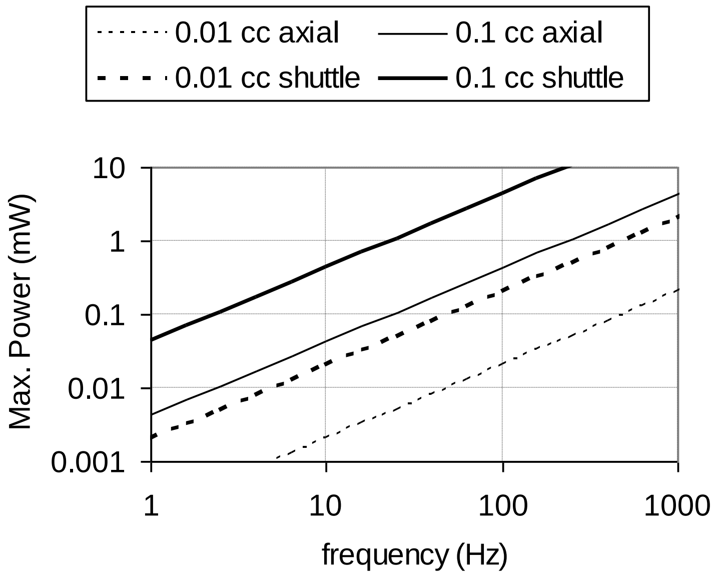
Power Density

- Depends on geometry: highest P/Vol for travel along long axis
- MEMS devices typically use plate geometry – not ideal
- In-plane motion: hard to achieve optimal travel range
- Off-axis travel can be a problem





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Implementation Issues: Resonance

Why use resonant device?

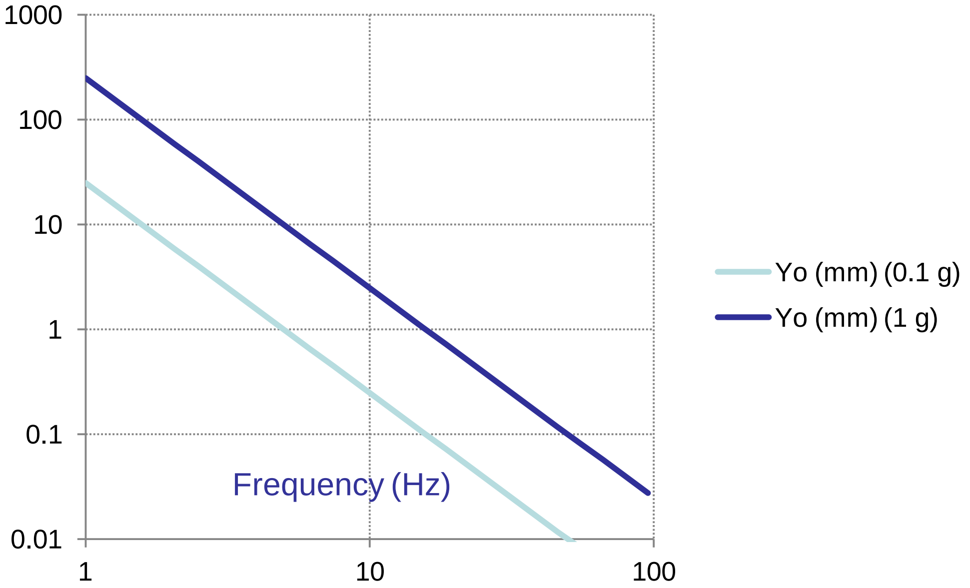
- Allows use of full internal range for low Y_o

Why not use resonant device?

- For low frequency application, $Y_o > z_o$ likely
- Low resonant frequency hard to achieve for small devices
- Not suitable for broadband or varying source frequency

Implementation Issues: Resonance

Input displacement vs frequency: low frequency range



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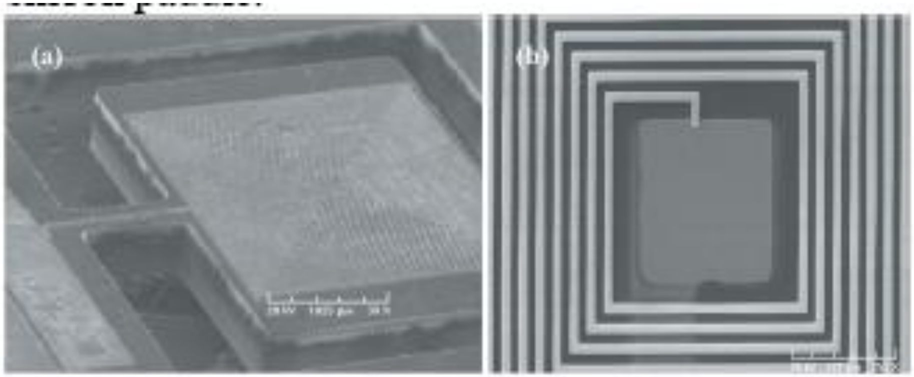
Transduction: Electromagnetic



Example:
Southampton/Tyndall Inst.

Advantages:

- Well understood system
- No source voltage needed (with permanent magnets)

Disadvantages

- Limited number of winding turns in MEMS: low voltages
- Low damping forces in low frequency operation

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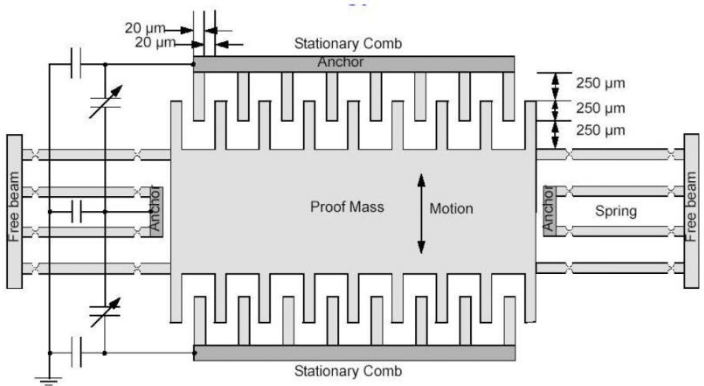
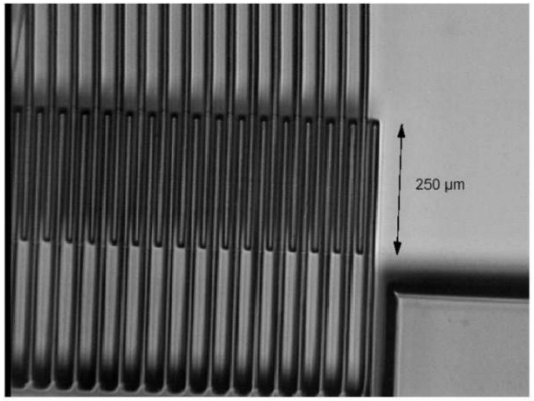
Transduction: Electrostatic





Example: MIT

Advantages:

- No special materials
- Suitable for MEMS scale

Disadvantages

- Needs priming voltage, or electret
- high output voltages typical

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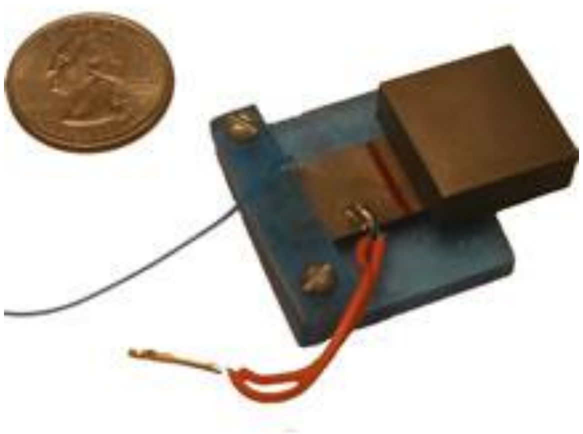
Transduction: Piezoelectric



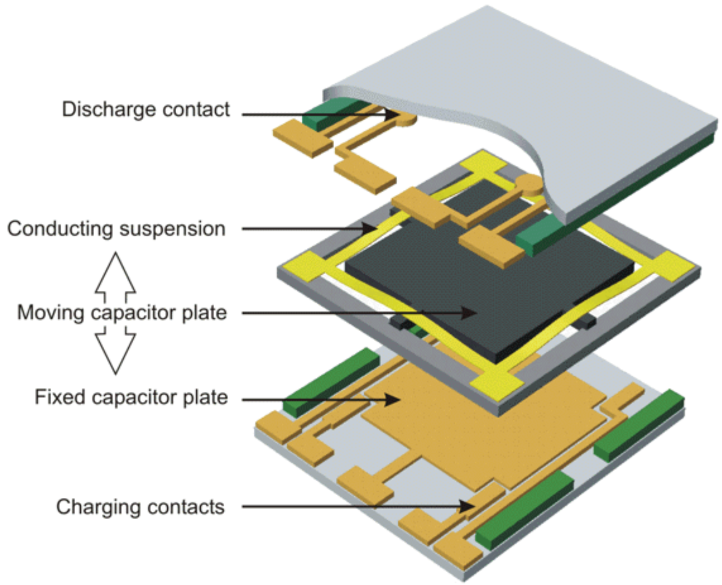
Example: UC Berkeley

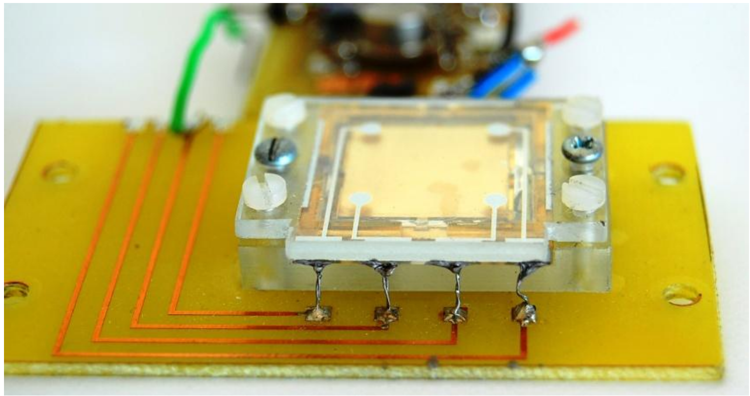
Advantages:
- High voltage even at low frequency
- Simple geometries

Disadvantages
- Low coupling coefficient
- integration of material

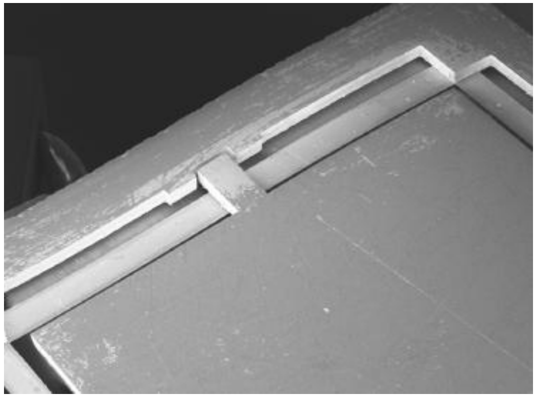
A Non-Resonant Electrostatic Harvester

- Si proof mass: whole wafer etching
- Polyimide suspension: low stiffness
- Wide frequency range of operation: suitable for body motion
- Self-synchronous: physical contact to charging and discharging terminals
- Size ≈ 12 × 12 × 1.5 mm



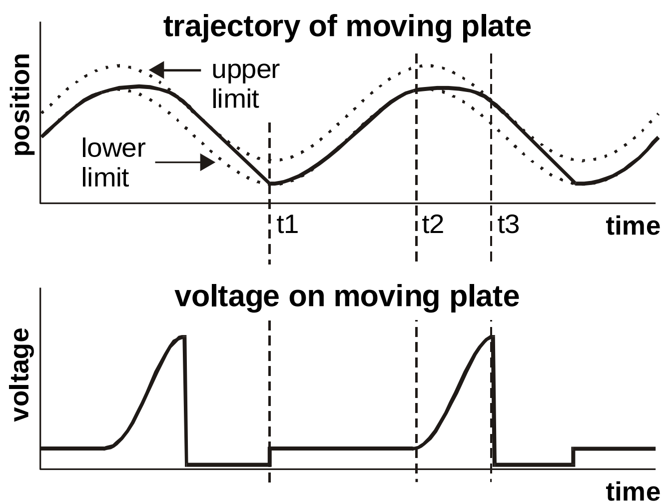


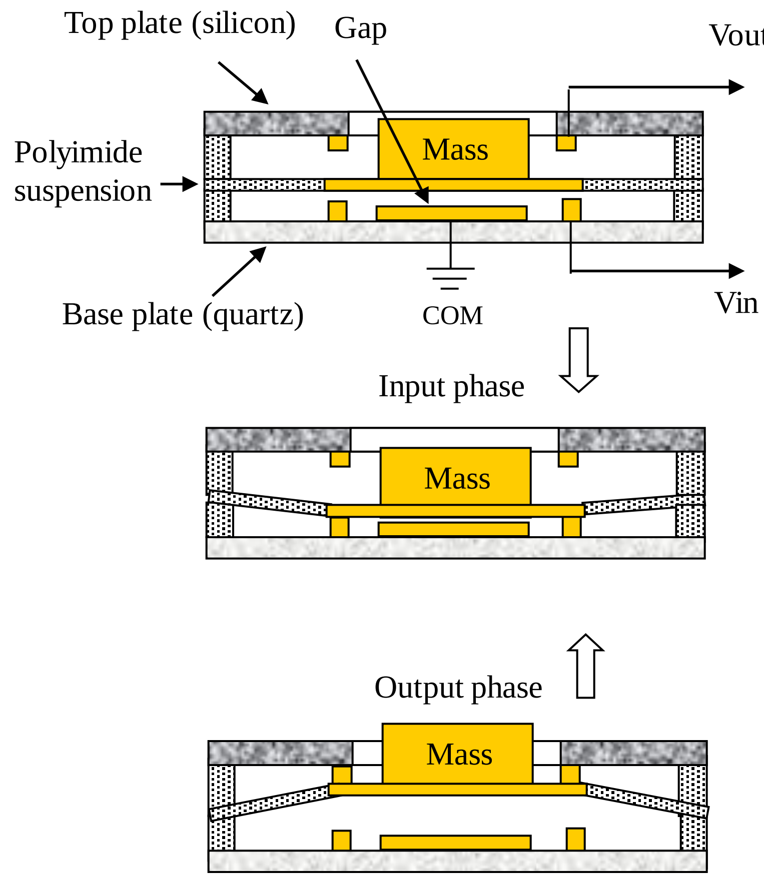
assembled generator



detail of moving plate

Non-Resonant Electrostatic Harvester 2





- Measured output > 2 μW at 20 Hz excitation
- Wide operating frequency range

Ref: Miao, P. et al. "MEMS inertial power generators for biomedical applications", Microsystem Techn. 12 (10-11), pp.1079-1083 (2006).

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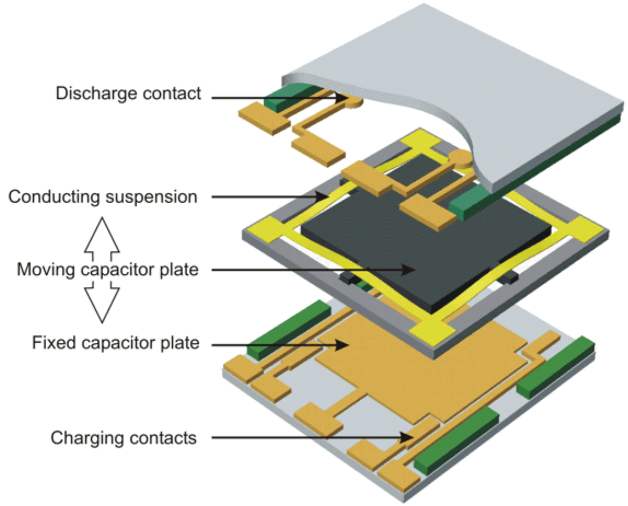
Non-Resonant Electrostatic Harvester: Problems

- Si density low – reduces *m*
- Travel range limited – movement is in short dimension
- Whole wafer etching expensive and limits integration potential
- Output in inconvenient large impulses



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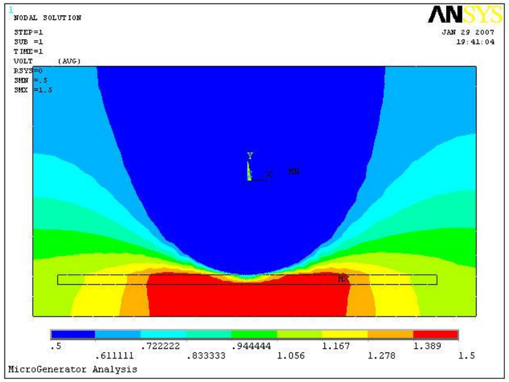
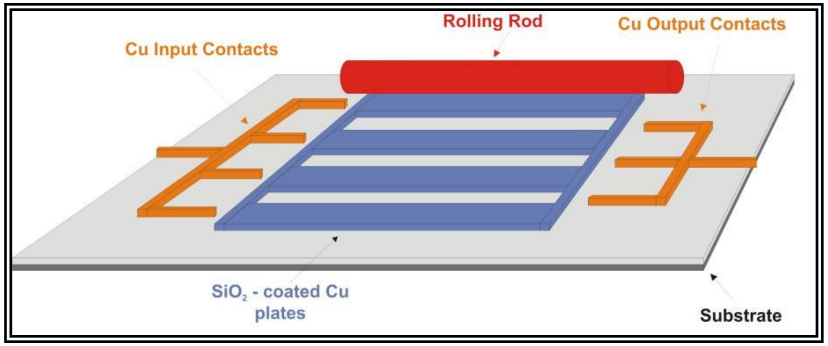
External Mass Electrostatic Harvester

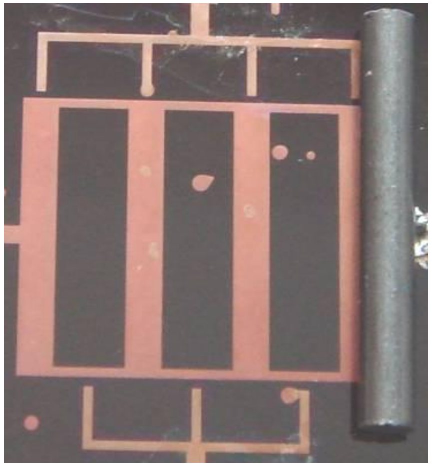
- Proof mass rolls on substrate
- Multiple charge-discharge cycles per transit
- No deep etching: fabrication simplicity
- Large mass and internal travel range



Electrostatic simulation



Schematic illustrating concept



Rolling mass on prototype device

Ref:

M. Kiziroglou, C. He and E.M. Yeatman, “Rolling Rod Electrostatic Microgenerator”, IEEE Trans. Industrial Electronics **56**(4), pp. 1101-1108 (2009).

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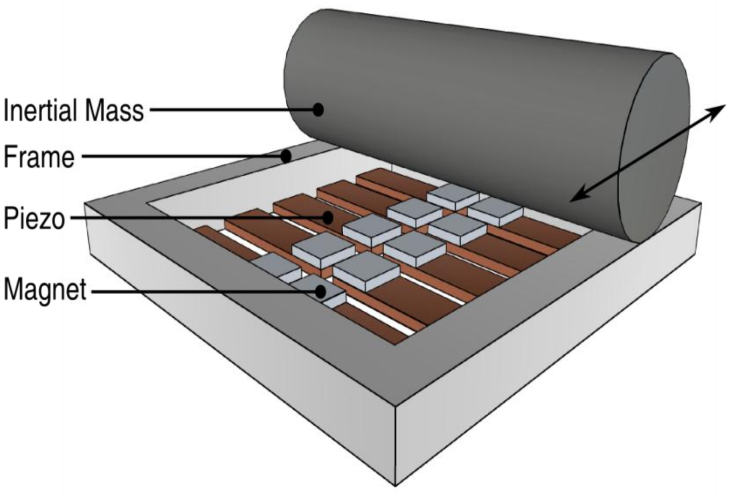
A Frequency Up-Converting Piezoelectric Harvester

- External rolling proof mass
- Distributed transduction by series of piezo beams
- Proof mass “plucks” beams by magnetic interaction
- Energy extracted as beams ring down: high electrical damping not needed

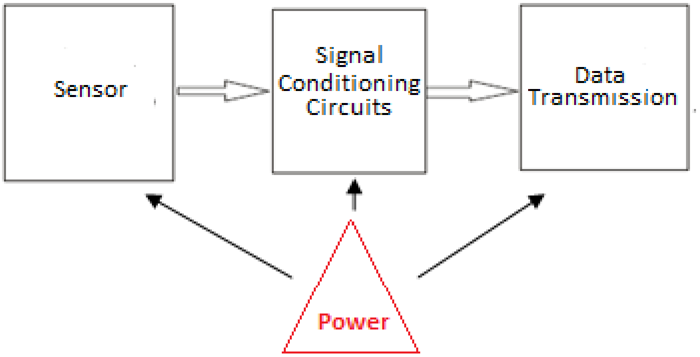


Ref:

P. Pillatsch, E.M. Yeatman & A.S. Holmes, “Piezoelectric Impulse-Excited Generator for Low Frequency Non-Harmonic Vibrations”, Proc. PowerMEMS 2011, Seoul, Nov. 2011, pp. 245-248.

Sensor Architecture for Micropower Operation

- Harvester power density inherently low for low frequency (e.g. human powered) applications
- Traditional architecture based on separate power and other modules
- Data processing and transmission modules most power intensive
- Solution: new approach to node architecture, mixing modules together



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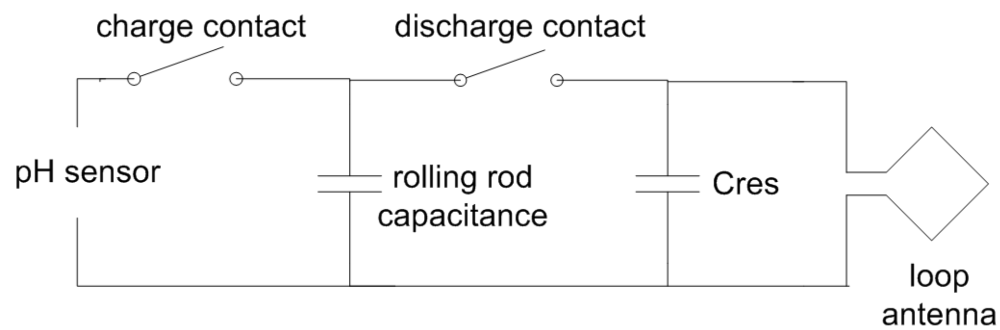
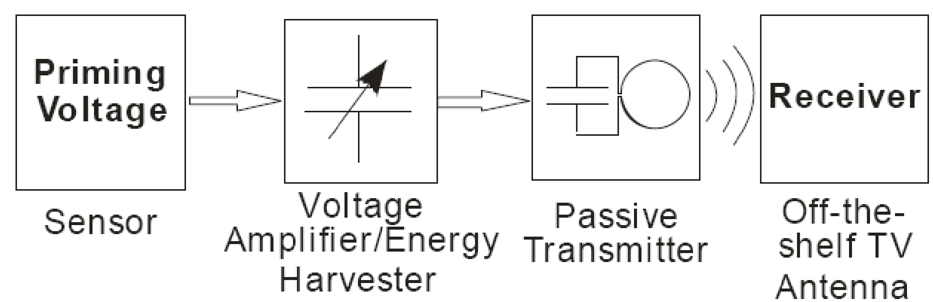
New Architecture

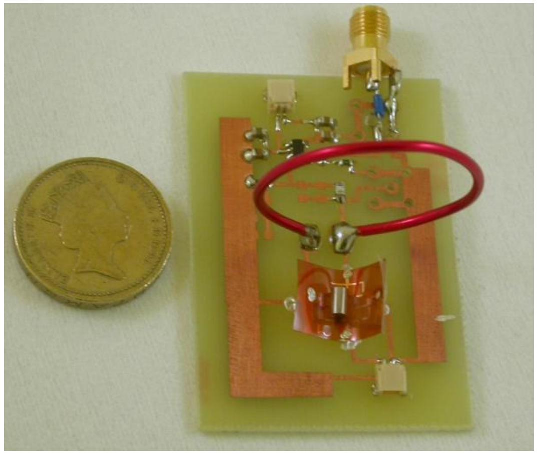
- Harvester connected between sensor output and transmitter
- Sensor acts as priming voltage, harvester as pulse former and energy amplifier
- Output pulses transmitted directly without further processing

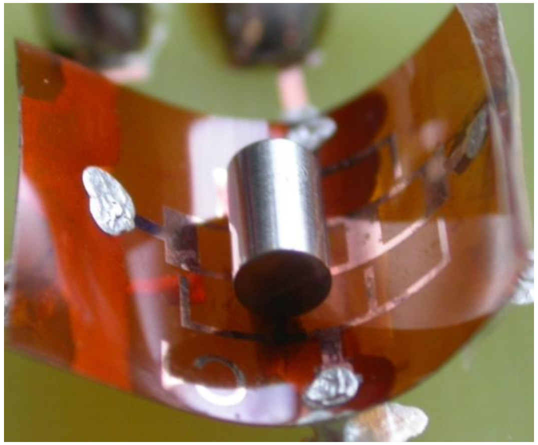




Fully Assembled Device

- Input from voltage supply representing output of sensors
- RF frequency determined by size of antenna loop: in this case 350 MHz
- Commercial off-the-shelf TV receiver employed for its broad bandwidth
- Higher frequency (> 1 GHz) will allow antenna loop close to harvester size (5 mm)





Ref:
C. He, M. Kiziroglou, D. Yates and E.M. Yeatman, “A MEMS Self-Powered Sensor and RF Transmission Platform for WSN Nodes”, IEEE Sensors **11**(12), pp.3437-3445 (2011).

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"Pure" Rotational Harvesters

Inertial Harvesters: power is limited by proof mass and travel range:

Maximum power = $m\omega^3 Y_o z_o/\pi$

Any alternatives?

yes, rotating proof mass:
limited motion range not inherent

Ref:
E.M Yeatman, "Energy Harvesting from Motion Using Rotating and Gyroscopic Proof Masses",
J. Mechanical Engineering Science **222** (C1), pp. 27-36 (2008).

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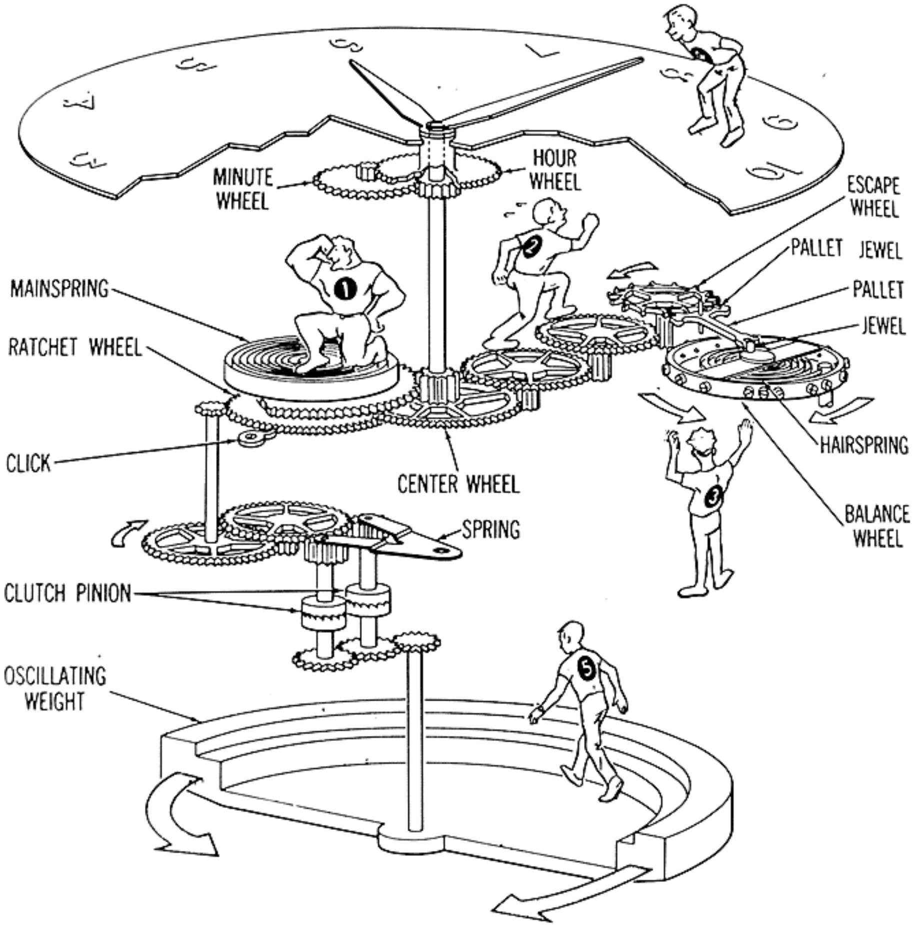
Rotating Mass Inertial Generator

Example #1: traditional self-winding watch



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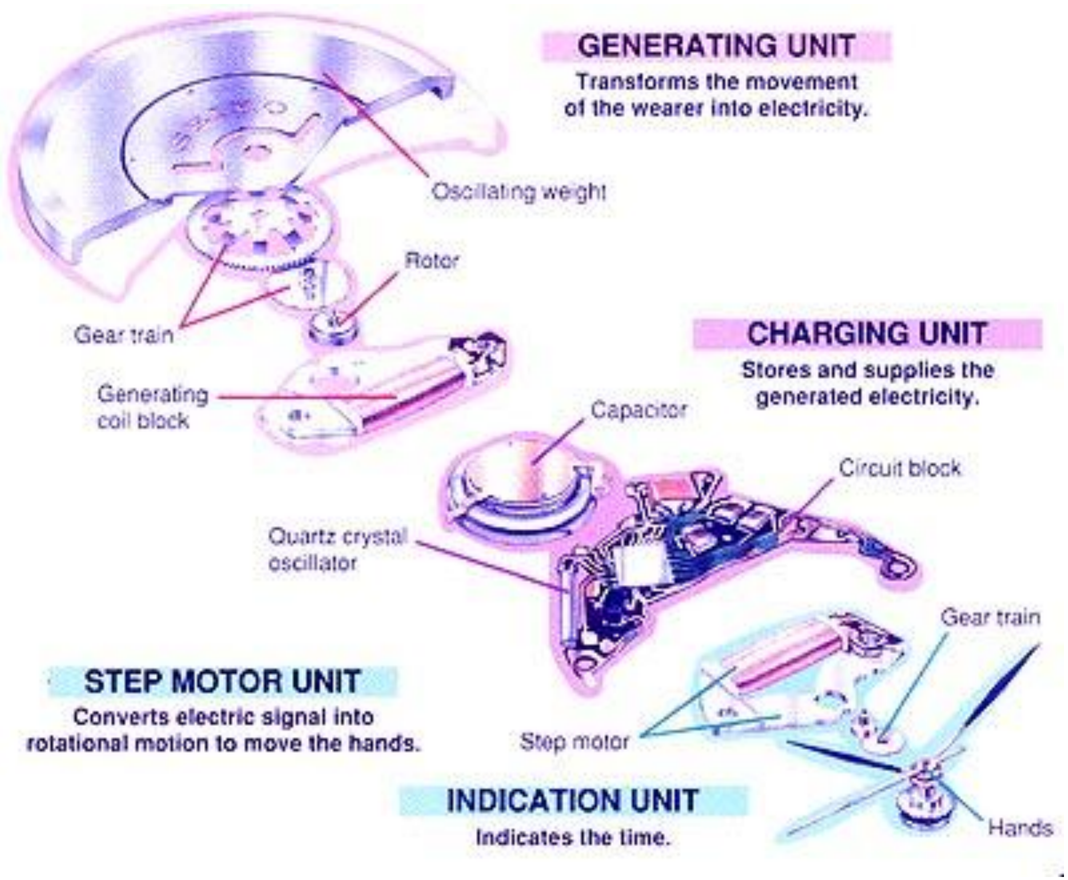
Rotating Mass Inertial Generator

Example #2: Seiko Kinetic



Rotating mass generator – two possible modes:

- driven by linear motion
- driven by rotating motion

Rotating mass generator – two possible modes:

- driven by linear motion
- driven by rotating motion

Semi-circle design of watch proof masses allows the former:

- Theoretically achievable power is similar to linear motion device: relative direction of mass and frame motion reverses on each half turn
- Advantage is in implementation practicalities.

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Rotating mass generator driven by rotating motion

Potential advantage: resonant enhancement

- Allows benefit of “unconstrained” internal amplitude
- Actual constraint is the need for a spring

Proposal : Rotating mass resonant generator

source motion amplitude θ_o , frequency ω
proof mass m, radius R

Achievable power:

$$P_{\max} = \frac{mR^2\theta_o^2\omega^3}{8}\sqrt{Q}$$

Compare: Rotating vs Linear resonant generator

Example: upper limb swinging at 1 Hz

- Linear: Y_o = 5 cm
- Rotating: θ_o = 25 deg
- Use mass of 1 g, radius = travel range = 0.5 cm

$$P_{\max} = \frac{mY_o Z_o \omega^3}{\pi}$$

vs.

$$P_{\max} = \frac{mR^2 \theta_o^2 \omega^3}{8}\sqrt{Q}$$

Result:

P_{lin} = 13 uW P_{rot} = 0.2 uW $\sqrt{Q}$

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Rotating vs Linear resonant generator

$P_{lin} = 13$ uW $P_{rot} = 0.2$ uW $\sqrt{Q}$

P_{rot} higher for $Q > 4000$

Technical Challenge:

- High Q for resonant rotating device requires spring with very high number of turns

Practical Challenge:

- High Q means high drive frequency dependence

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Overcoming the Mass Limit

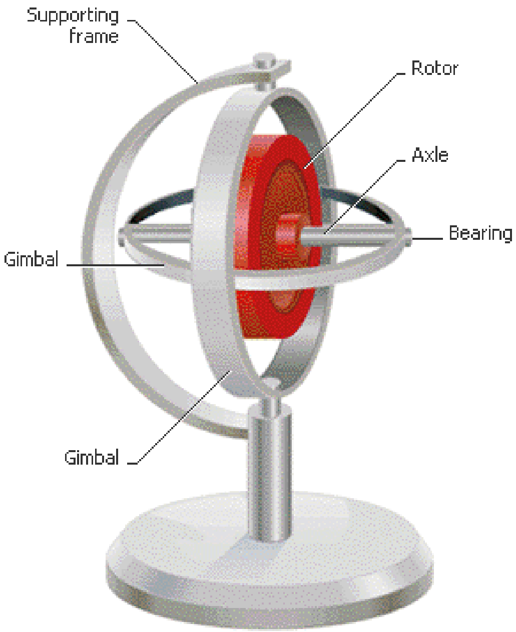
How else can rotating motion be used in inertial generation?

Overcoming the Mass Limit

How else can rotating motion be used in inertial generation?

What about driving the rotation actively?

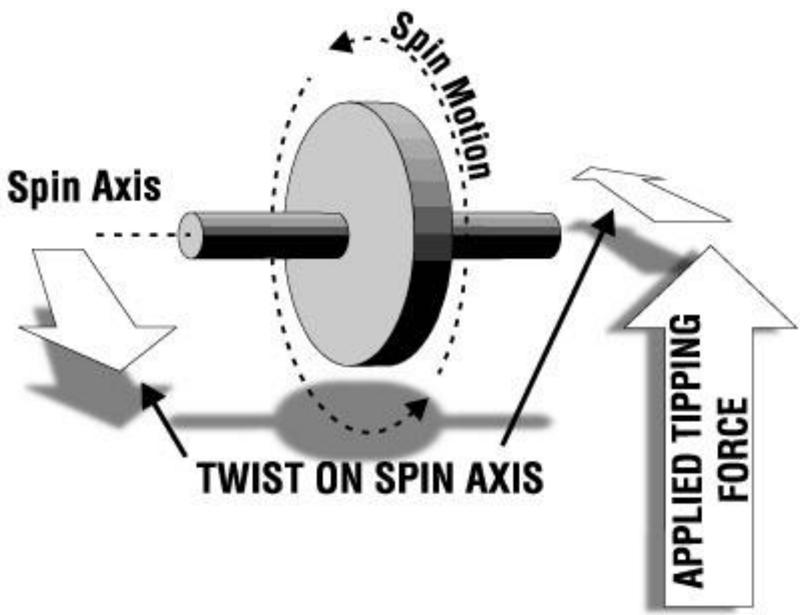
Proposal: Gyroscopic power generation



Gyroscopic power generation

Basic principle: for moment of inertia I rotating at ω_s and tipped at ω_p :

torque $T = I\omega_s\omega_p$

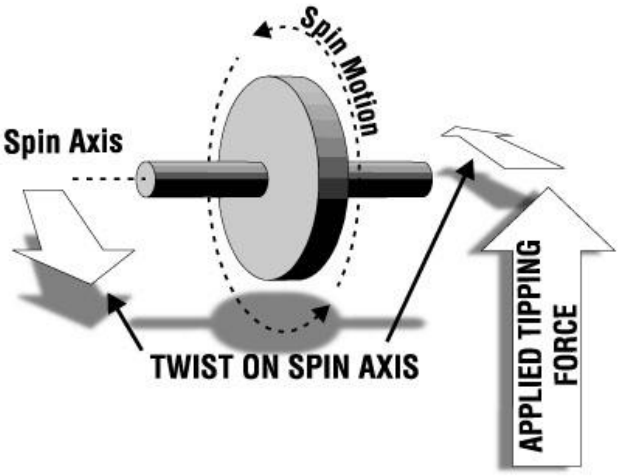


Gyroscopic power generation

Mechanism: couple the rocking frame to the gyroscopic body by the energy extracting damper (electrostatic…)

For disk spun at ω_s and rocked at ω_o, achievable power:

$$P_{gyr} = \frac{1}{4} m R^2 \theta_o^2 \omega_o^2 \omega_s$$



Gyroscopic power generation

Opportunity: power output rises with spin speed

Limitation: need to subtract drive power

- Depends on drive speed; optimum drive speed thus determined by Q

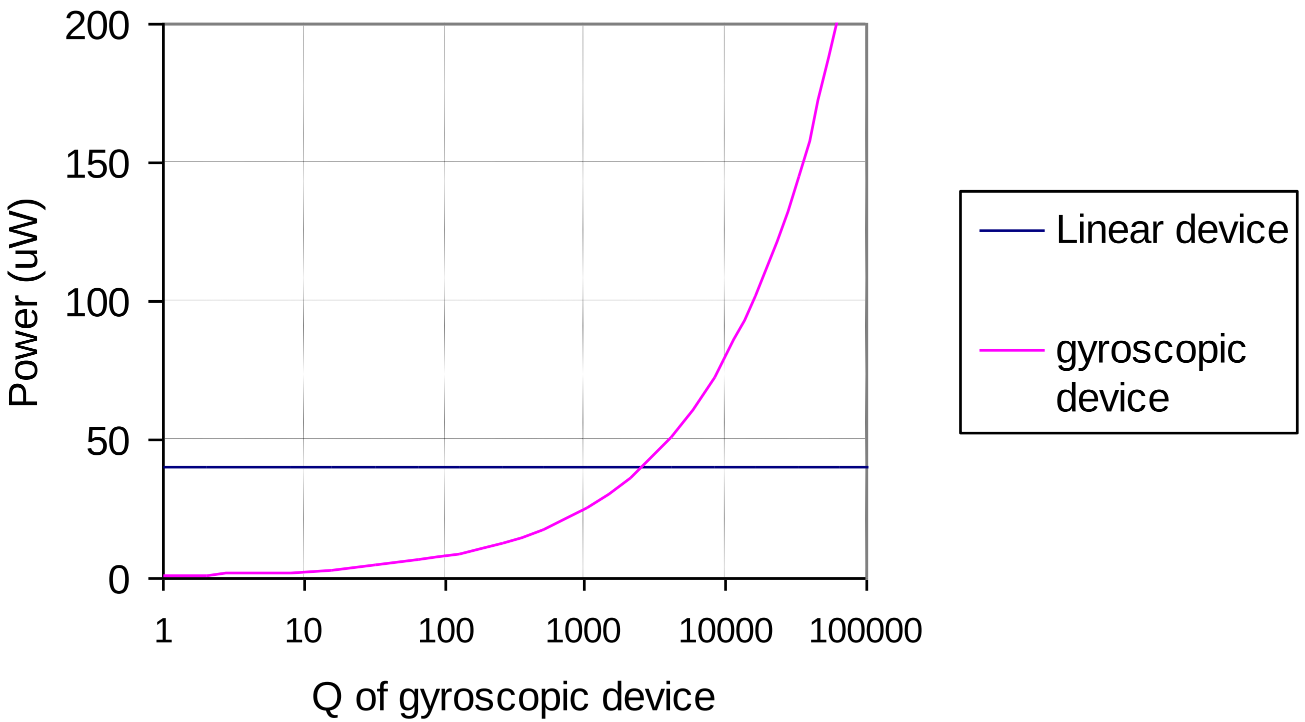
Gyroscopic power generation

Net power:

$$P_{gyr} = \frac{\sqrt{2\pi/3}}{3} mR^2\theta_o^2\omega^3\sqrt{Q}$$

About 4x resonant rotating (passive) case

Gyroscopic power generation



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Gyroscopic power generation

How to implement in MEMS? High quality spinning bearings not really available.

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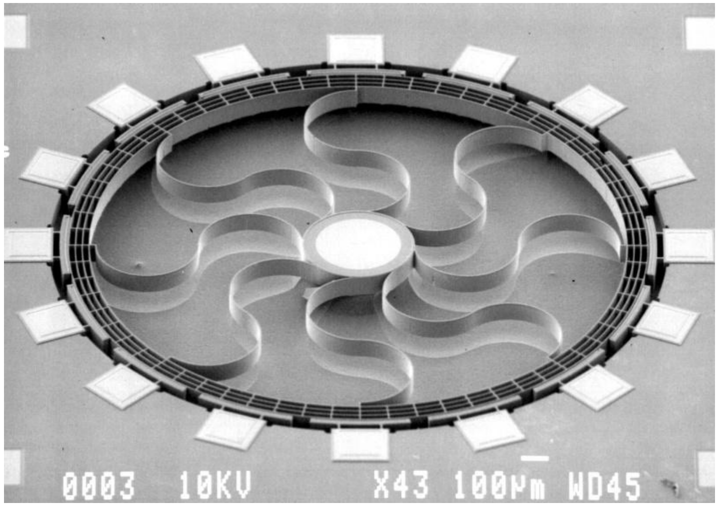
Gyroscopic power generation

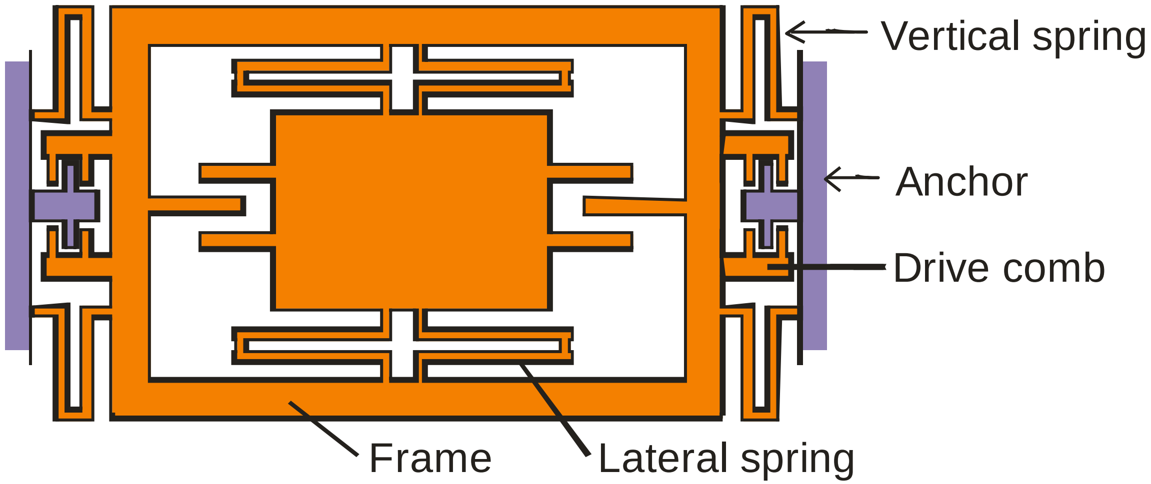
How to implement in MEMS? High quality spinning bearings not really available.

- Solution: well known format for MEMS gyros
    - Vibrating gyro



Gyroscopic power generation

- Proposed format: linear vibration on two axes, one for drive, one for pick-off;
- Same as gyro sensor except pick-off extracts energy, not signal



after Fedder et al

Conclusions

- Basic mechanics sets strict limits on achievable power from inertial harvesters
- Ultimate power density drops as devices shrink
- Form factor, resonance and choice of transduction are important considerations
- Rotating harvesters can offer some ways around the basic limits

Thanks:

Paul Mitcheson, Tzern Toh, Peng Miao, Michalis Kiziroglou, Cairan He, David Yates, Andrew Holmes, Pit Pillatsch

EPSRC, European Commission

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