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Miniaturising Motion Energy Harvesters: Limits and Ways Around Them

Eric M. Yeatman

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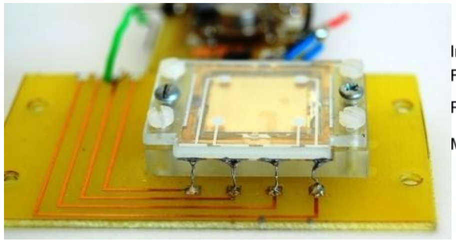
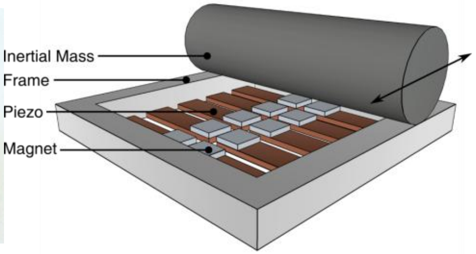
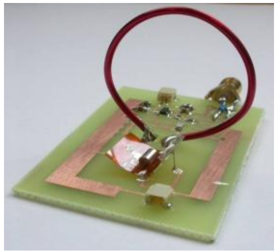
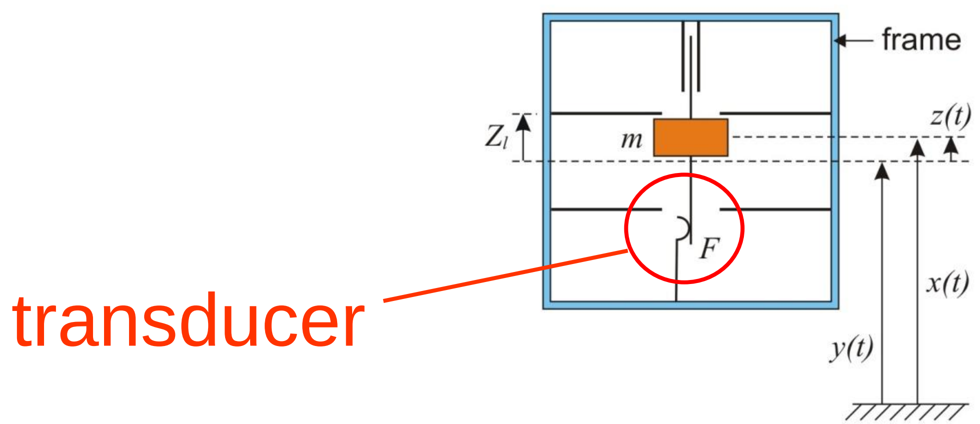





Inertial Harvesters

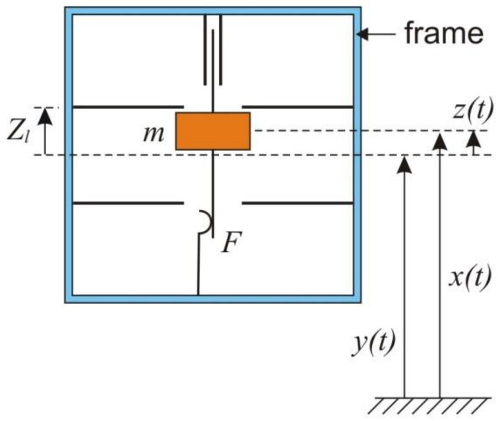
- Mass mounted on a spring within a frame
- Frame attached to moving "host" (person, machine…)
- Host motion vibrates internal mass
- Internal transducer extracts power



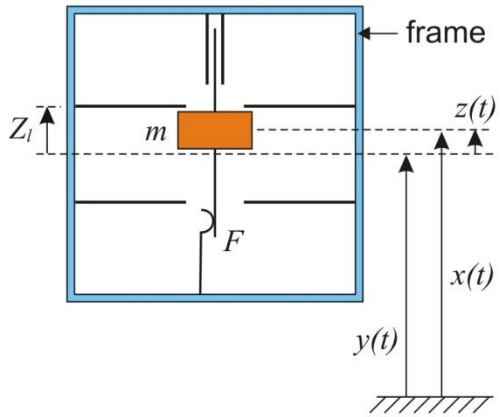
Available Power from Inertial Harvesters

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 $P = 2W/T = m\omega^3 Y_o z_o/\pi$



Ref: Mitcheson, P. et al. “Architectures for vibration-driven micropower generators”, J. Microelectromechanical Systems 13(3), pp. 429-440 (2004).

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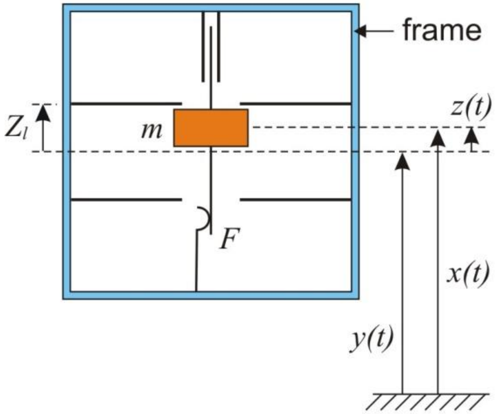
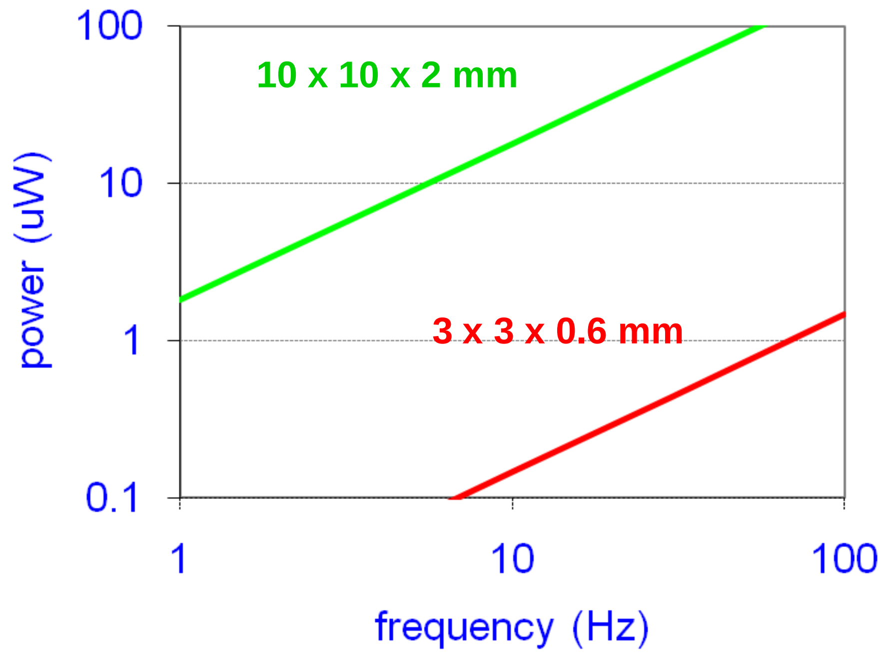
Implications for Scaling

- 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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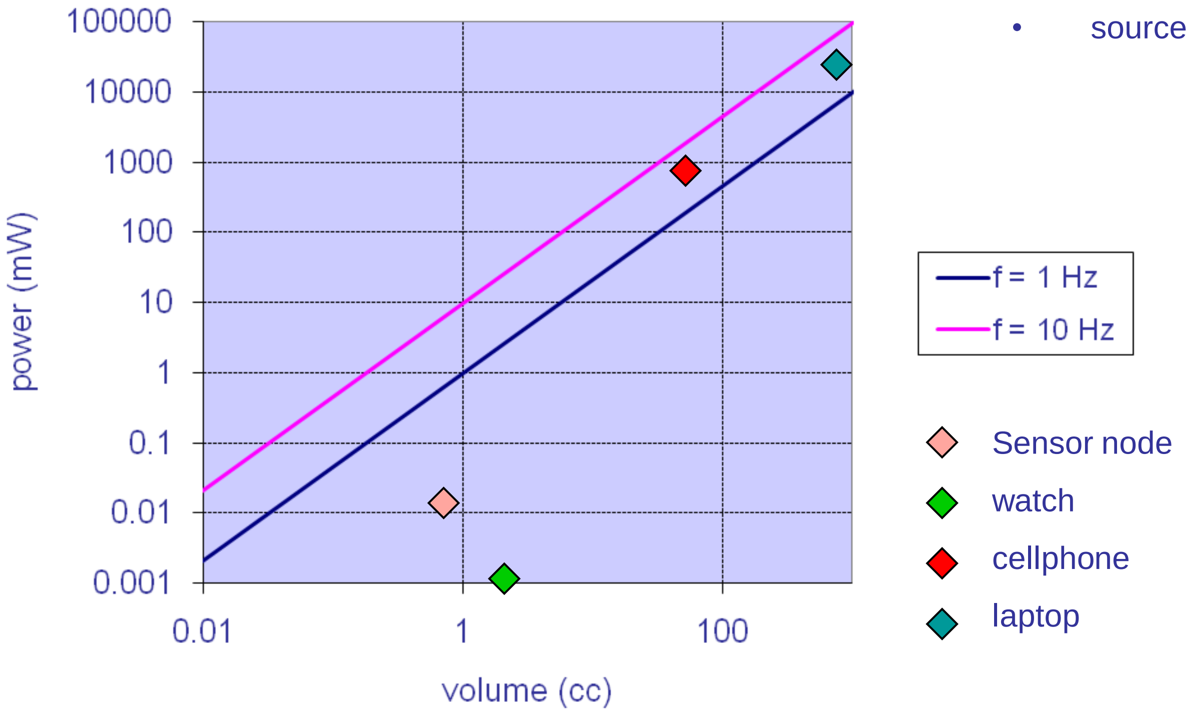
Achievable Power Relative to Applications



Plot assumes:

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

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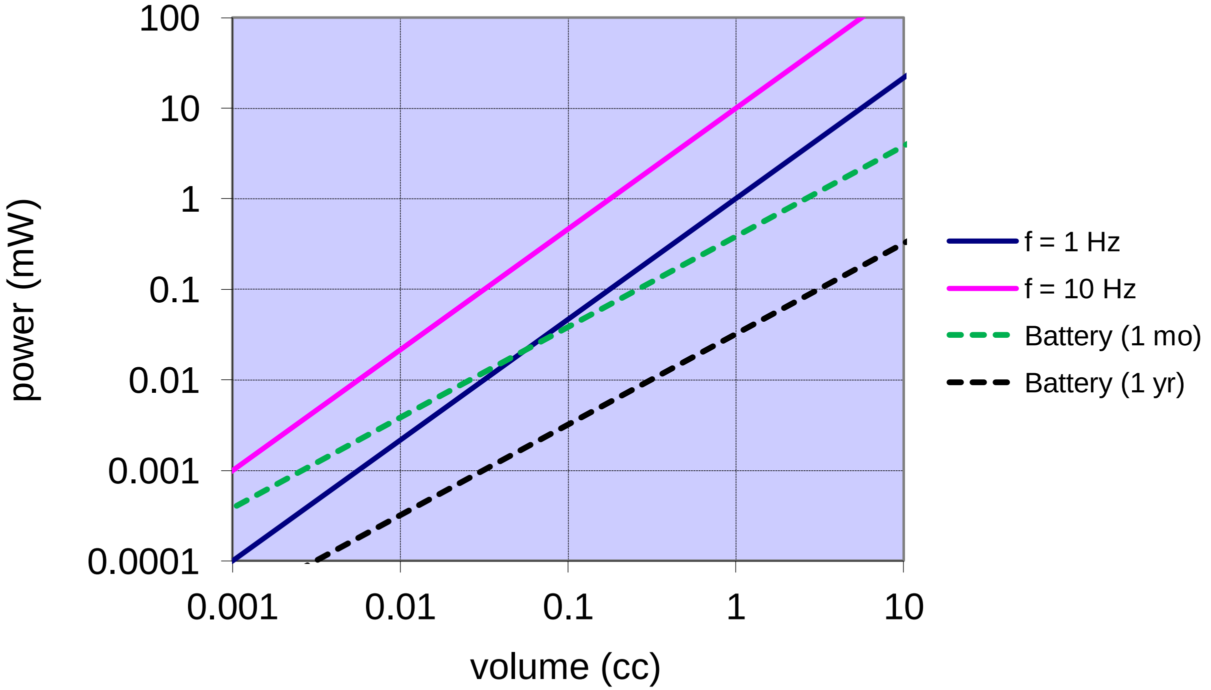
Possible Power Relative to Batteries

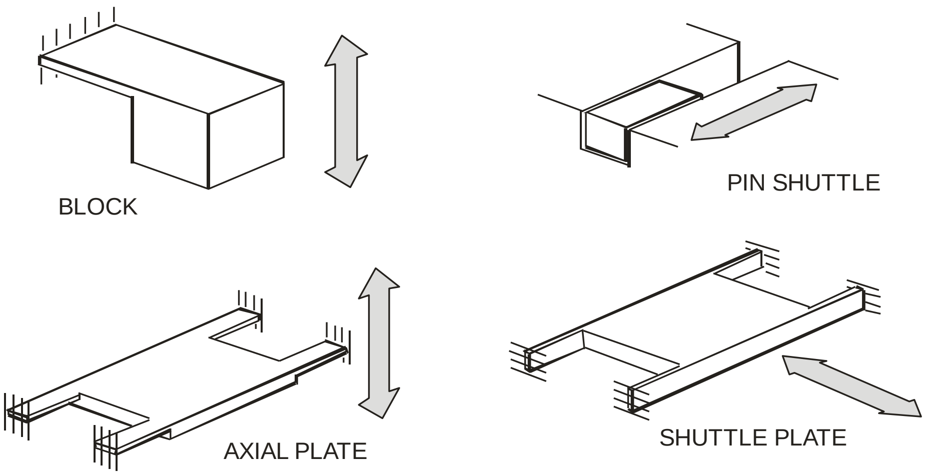


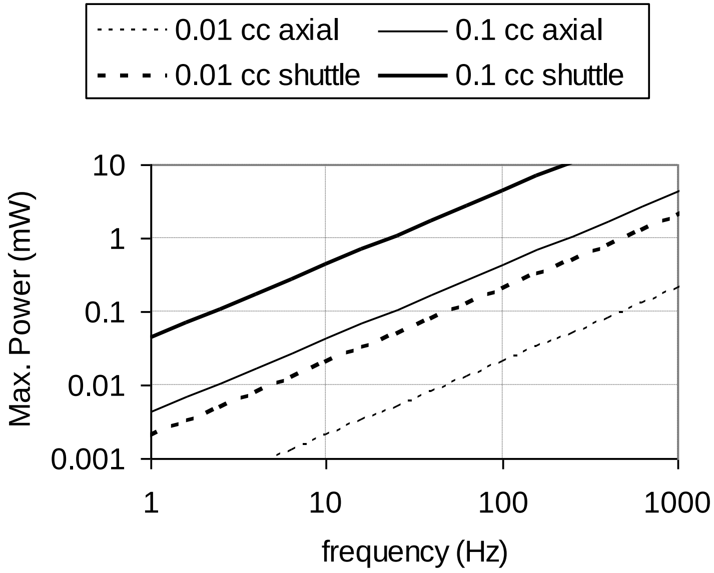
Plot assumes:

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

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?

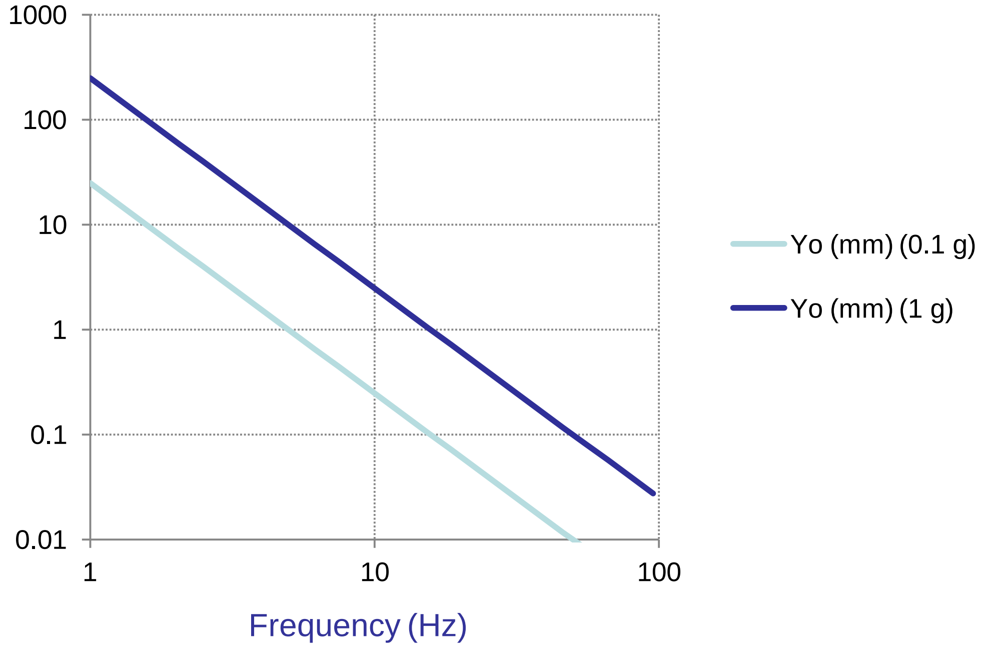
- Allows use of full internal range for low Y_o

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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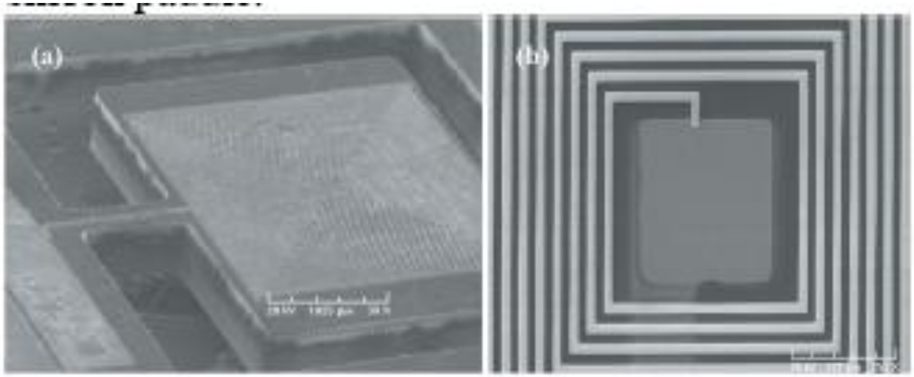
Transduction: Electromagnetic



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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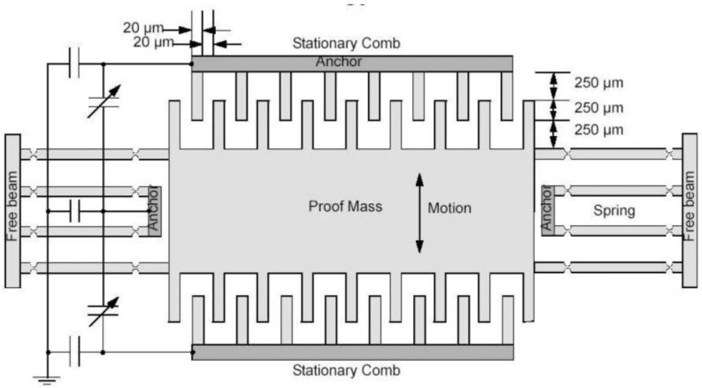
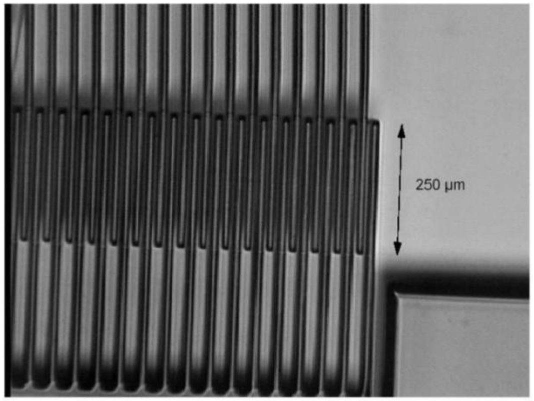
Transduction: Electrostatic





Example: MIT

Advantages:
- No special materials
- Suitable for MEMS scale

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

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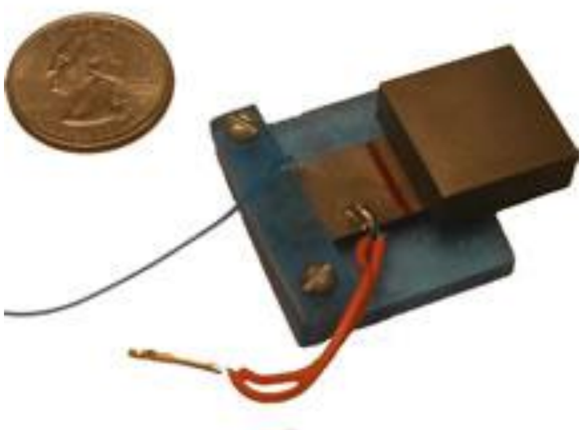
Transduction: Piezoelectric



Example: UC Berkeley

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

Disadvantages
- Low coupling coefficient
- integration of material

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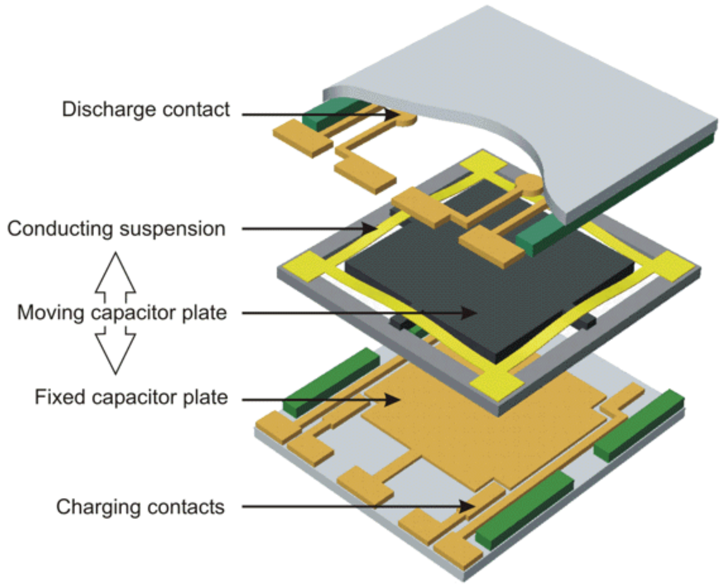
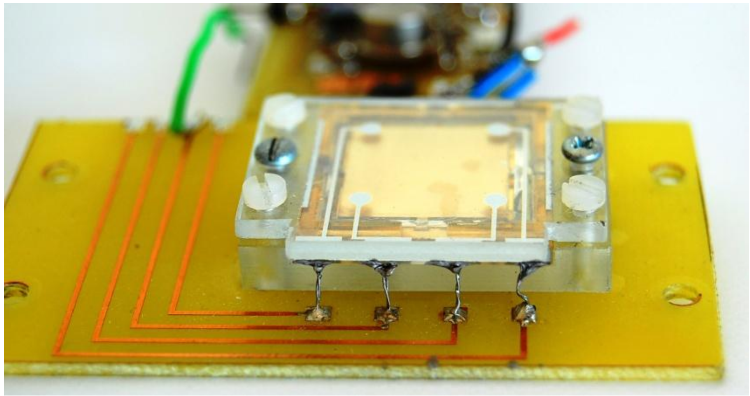
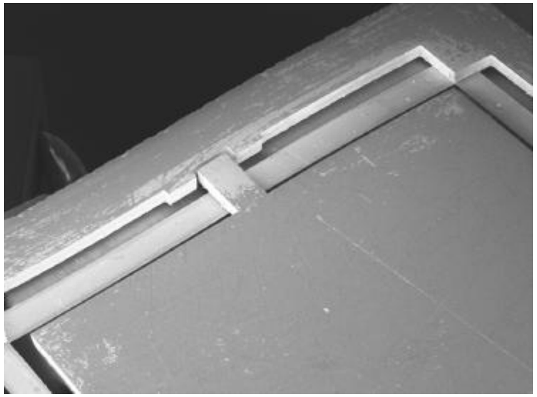
A Non-Resonant Electrostatic Harvester

- 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



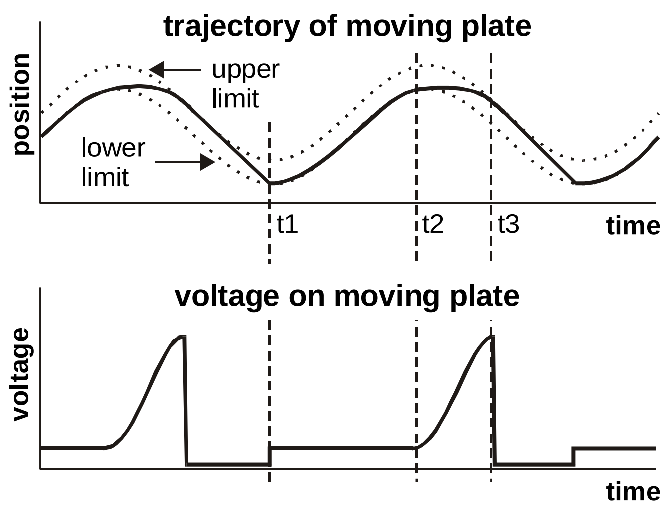


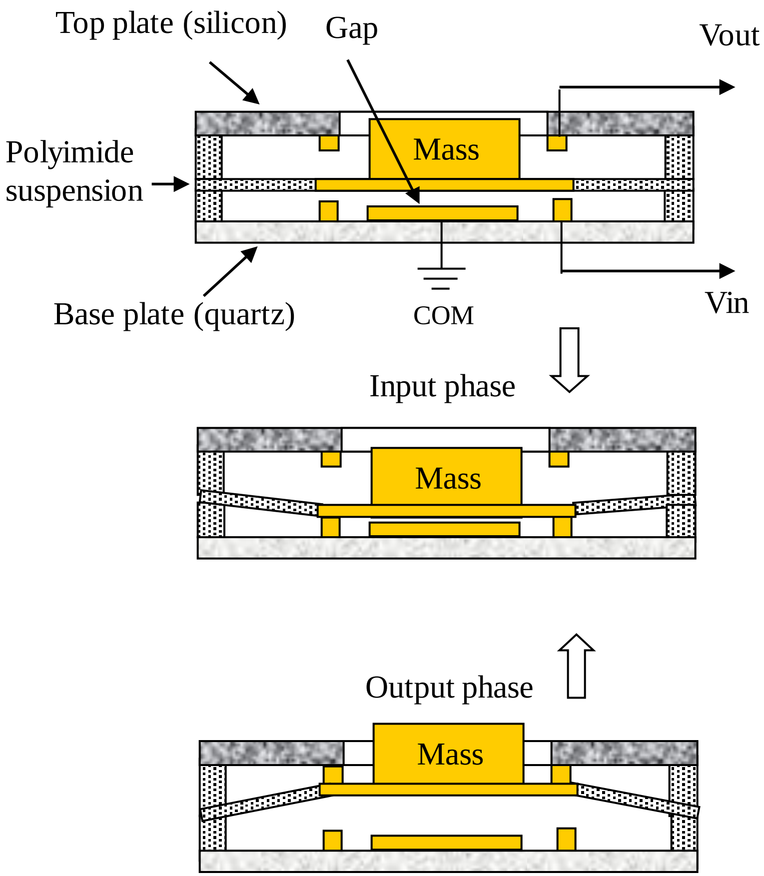
assembled generator



detail of moving plate

Non-Resonant Electrostatic Harvester 2



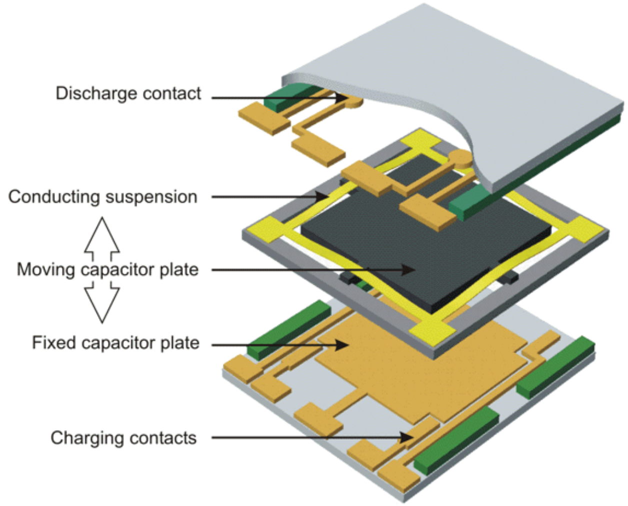


- Measured output > 2 μW at 20 Hz excitation
- Wide operating frequency range

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

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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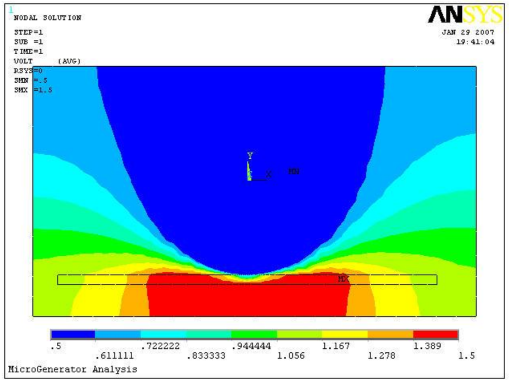
External Mass Electrostatic Harvester

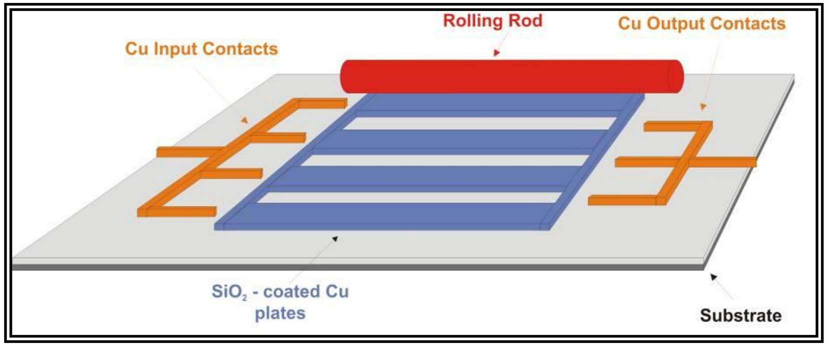
- Proof mass rolls on substrate
- Multiple charge-discharge cycles per transit
- No deep etching: fabrication simplicity
- Large mass and internal travel range

But:

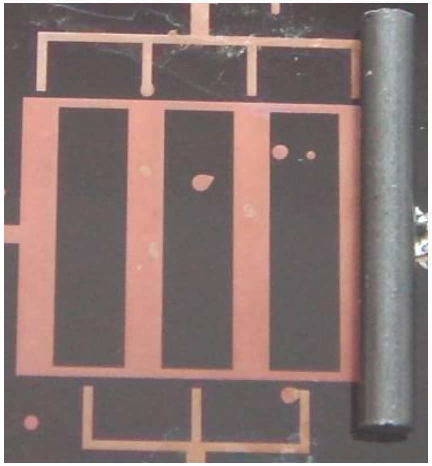
- Very low capacitances & capacitance ratios
- Thus, low power for given priming voltage



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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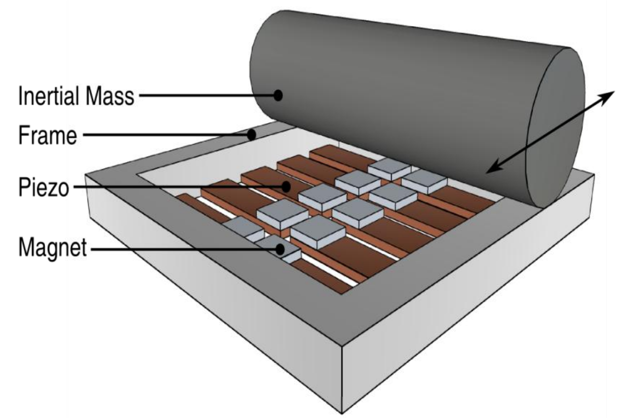
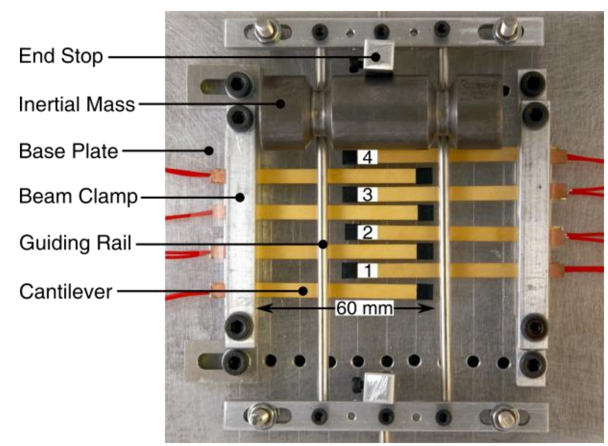
Overcoming Low Electro-mechanical Coupling: Frequency Up-Converting Piezoelectric Harvester

- 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

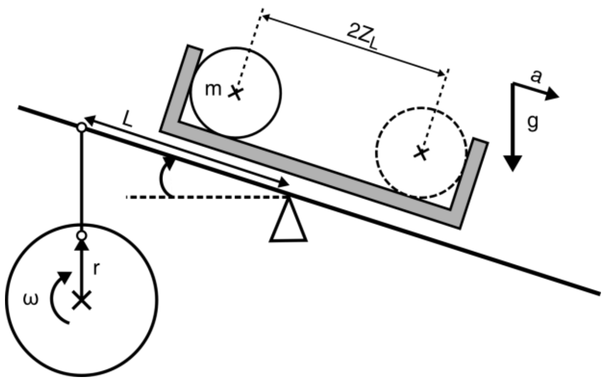




Ref:

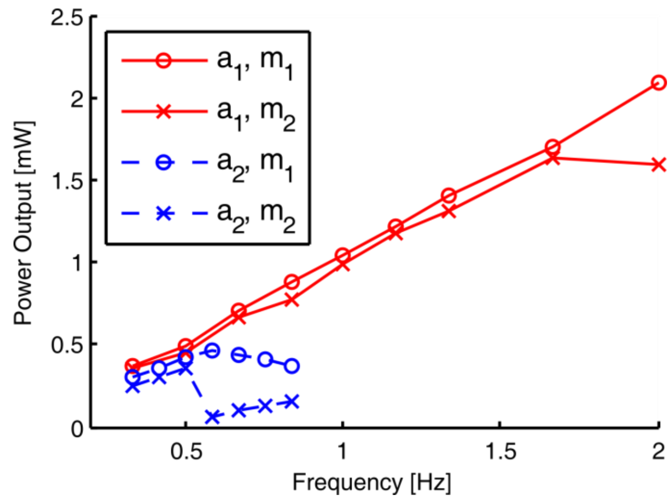
P. Pillatsch, E.M. Yeatman & A.S. Holmes, “Piezoelectric Impulse-Excited Generator for Low Frequency Non-Harmonic Vibrations”, Proc. PowerMEMS 2011, Seoul, Nov. 2011, pp. 245-248.

Frequency Up-Converting Piezoelectric Harvester

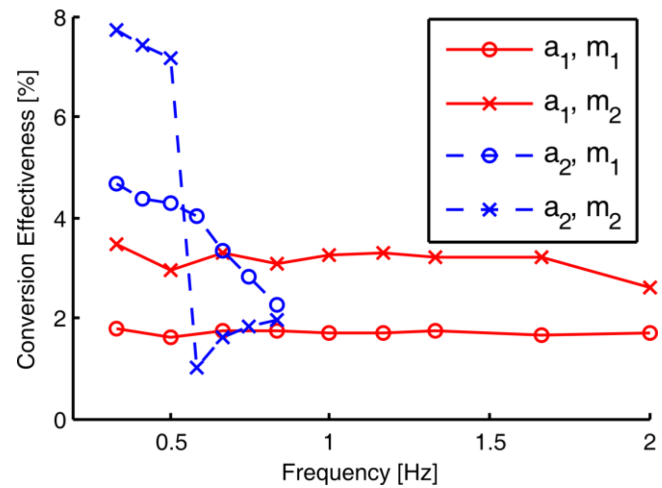


4 test configurations:

- $a_1 = 2.72\ m/s^2$
- $a_2 = 0.873\ m/s^2$
- $m_1 = 0.285$ kg
- $m_2 = 0.143$ kg



- Operation over a wide frequency range (6:1) demonstrated at higher acceleration
- Effectiveness reasonable for first design
- Power density of 4-13 $\mu W/cm^3$ for lighter proof mass
- Scalable design



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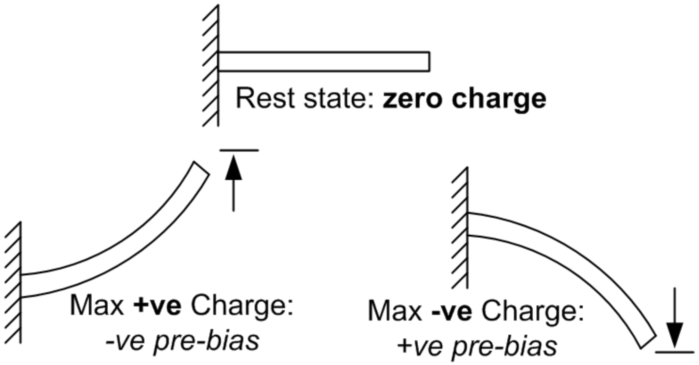
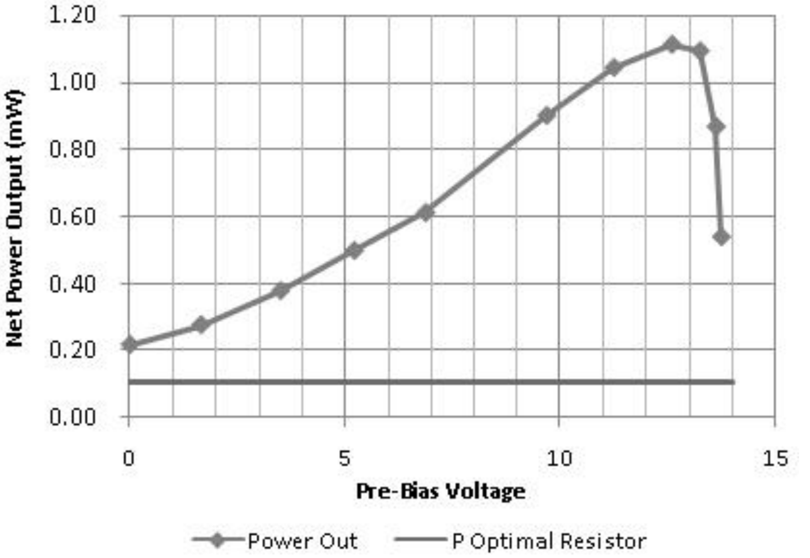
Overcoming Low Electro-Mechanical Coupling: Active Interface Circuits

- Piezo devices limited by high output capacitance
- Difficult to match load impedance – leads to weak damping factor
- Concept is to synchronously precharge the piezo cell to increase damping force





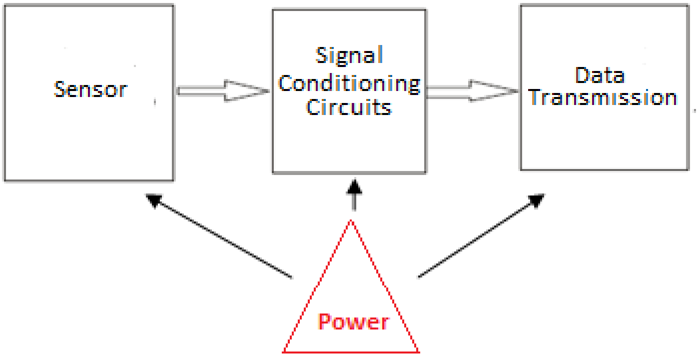
Re-designing Sensor Architecture for Harvester-Powered Operation

- 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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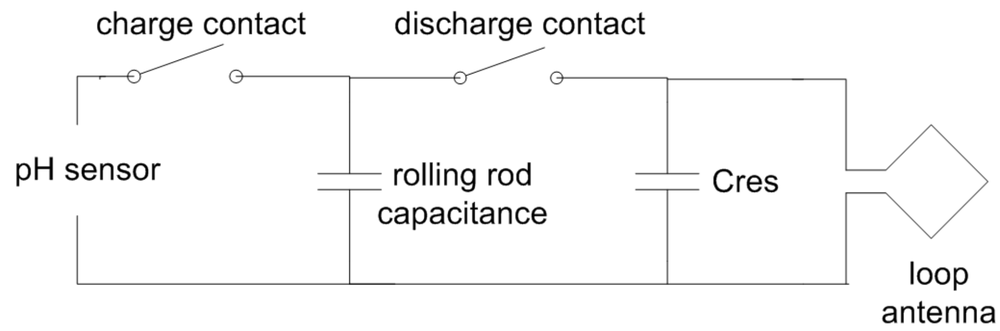
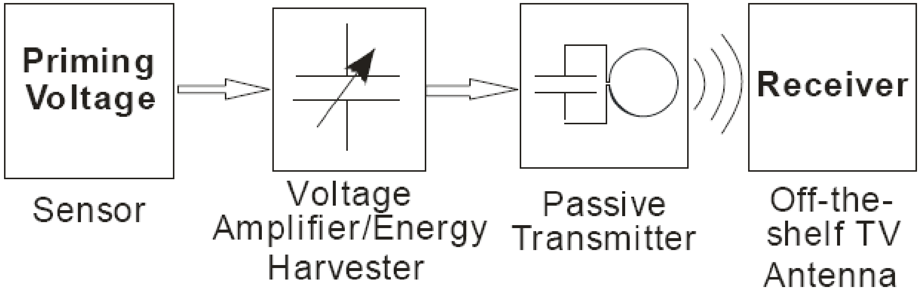
New Architecture

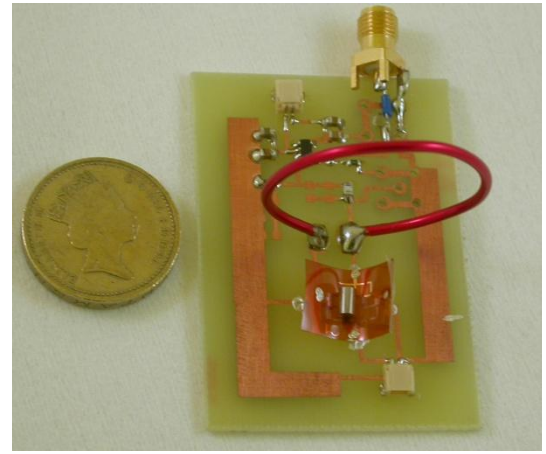
- Harvester connected between sensor output and transmitter
- Sensor acts as priming voltage, harvester as pulse former and energy amplifier
- Output pulses transmitted directly without further processing

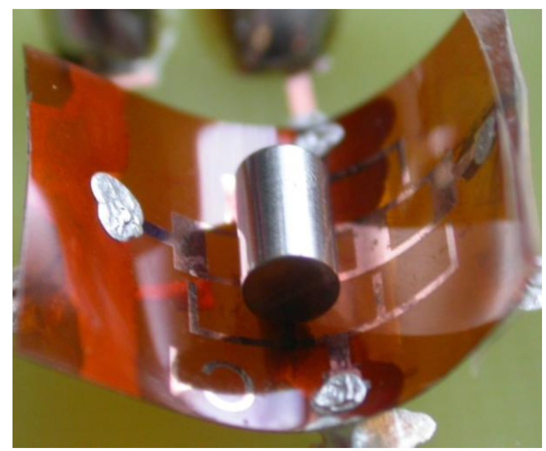




Fully Assembled Device

- 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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Overcoming Displacement Limit: 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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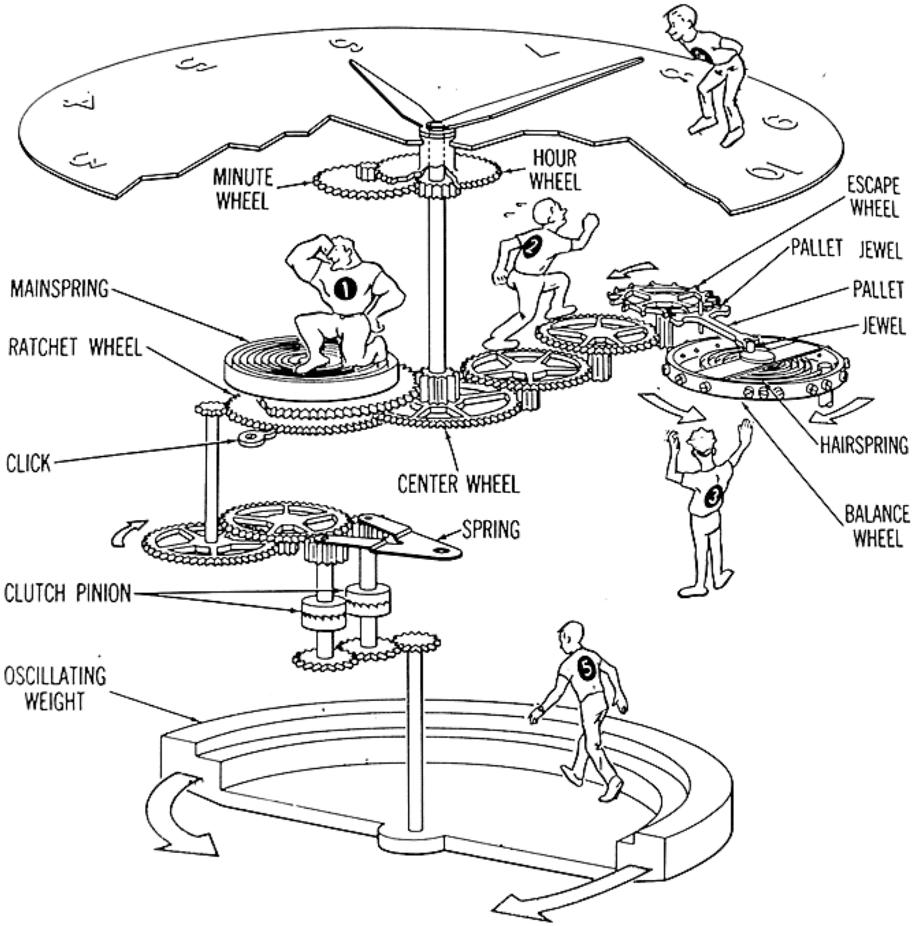
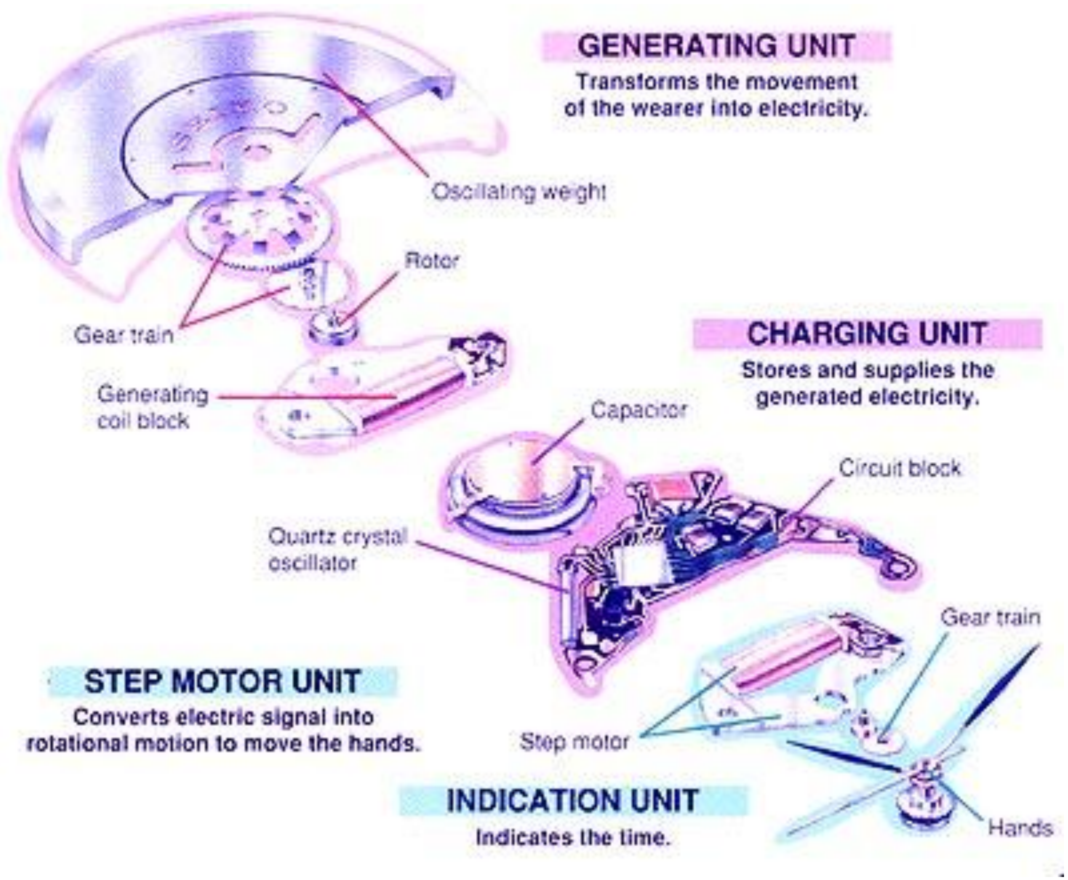
Rotating Mass Inertial Generator

Example #1: traditional self-winding watch



Rotating Mass Inertial Generator

Example #2: Seiko Kinetic



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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.

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

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Proposal : Rotating mass resonant generator

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

Achievable power:

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

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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

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

vs.

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

Result:

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

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

Overcoming the Mass Limit

How else can rotating motion be used in inertial generation?

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Overcoming the Mass Limit

How else can rotating motion be used in inertial generation?

What about driving the rotation actively?

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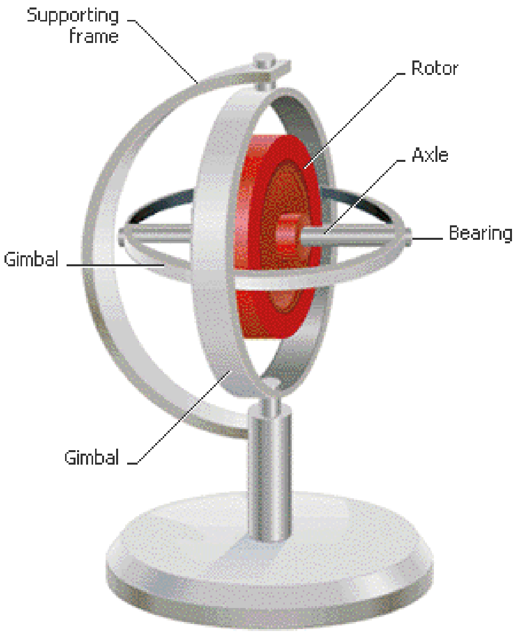
Proposal: Gyroscopic power generation



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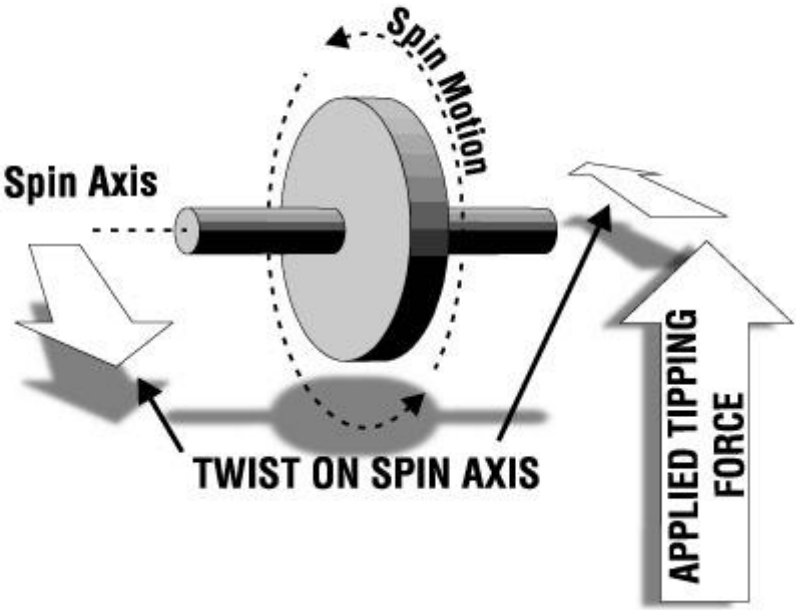
Gyroscopic power generation

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

torque $T = I\omega_s\omega_p$

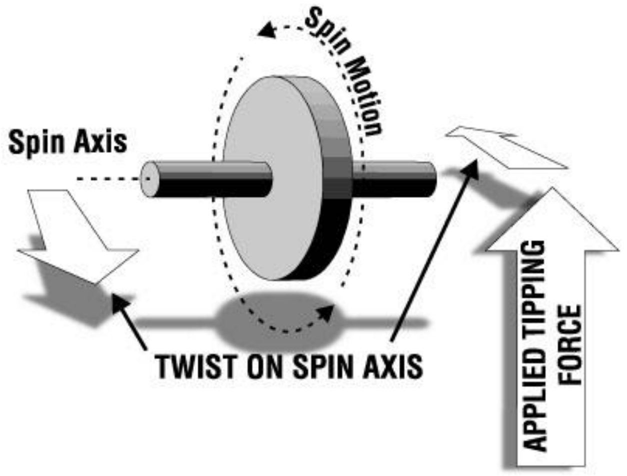


Gyroscopic power generation

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:

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



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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

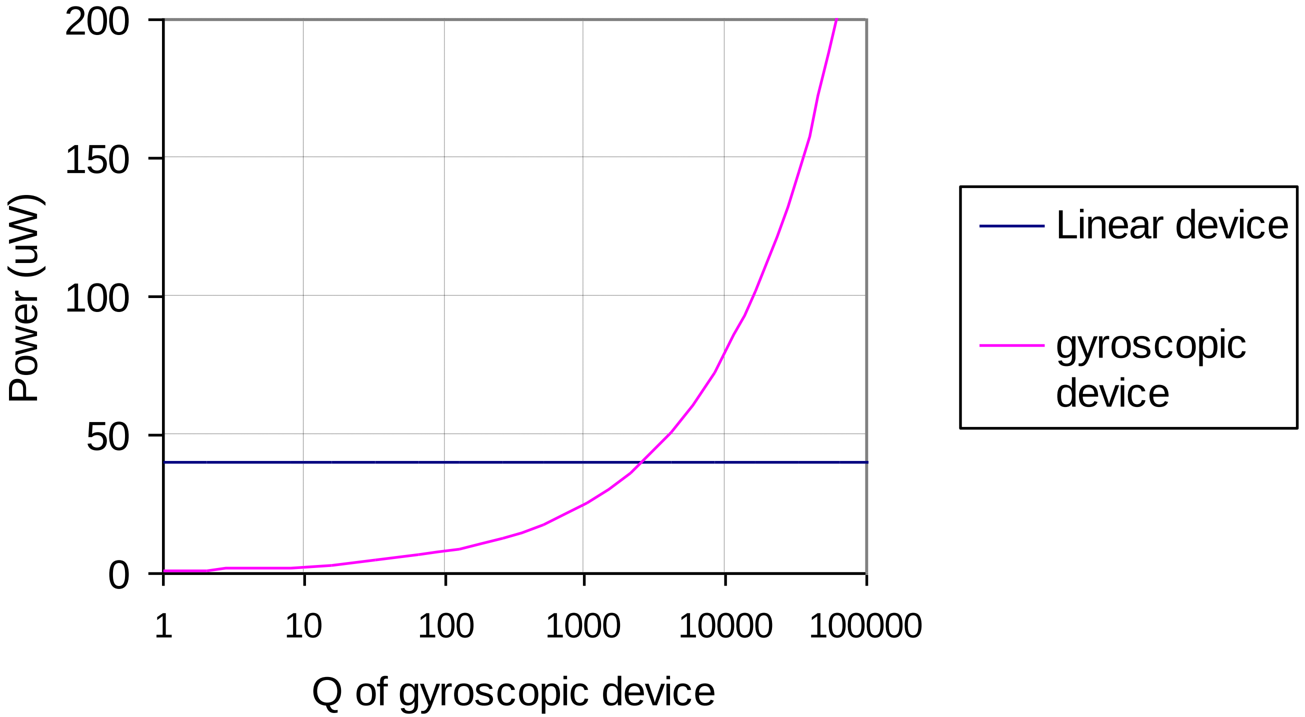
Gyroscopic power generation

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



Gyroscopic power generation

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

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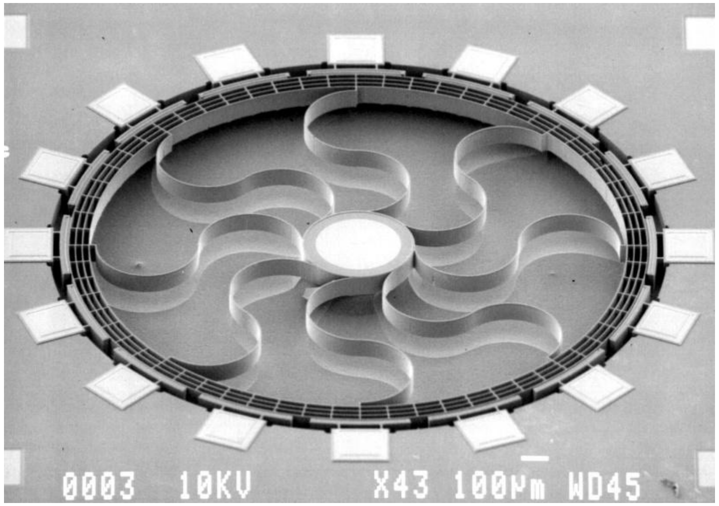
Gyroscopic power generation

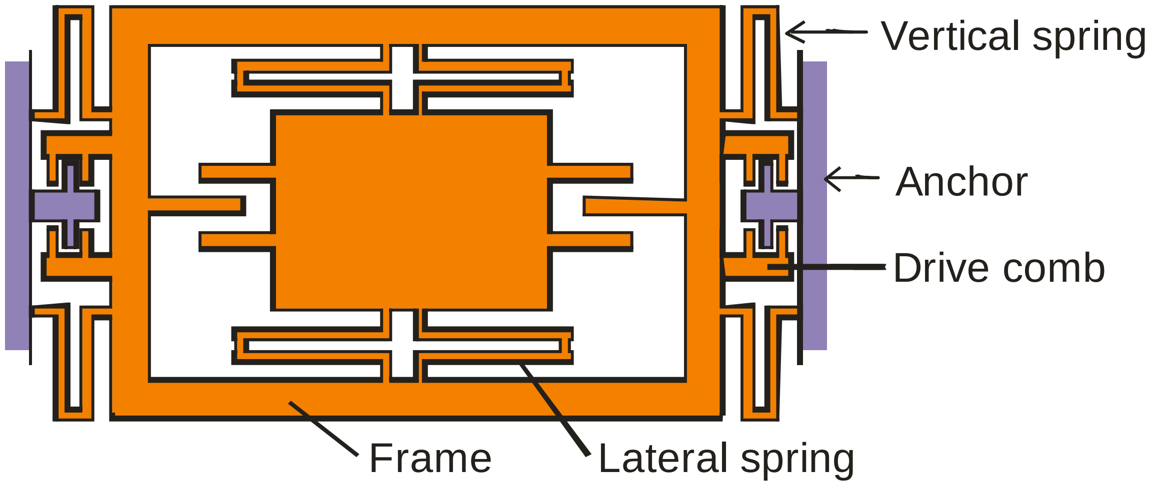
How to implement in MEMS? High quality spinning bearings not really available.

- 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

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

EPSRC, European Commission

Contact: e.yeatman@imperial.ac.uk

Review Paper: P. D. Mitcheson, E. M. Yeatman, G.K. Rao, A. S. Holmes & T. C. Green, “Energy Harvesting from Human and Machine Motion for Wireless Electronic Devices”, Proc. IEEE 96(9), pp. 1457-1486 (2008).