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Miniature Motion Energy Harvesters with Rotating Mechanisms

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NIPS Summer School
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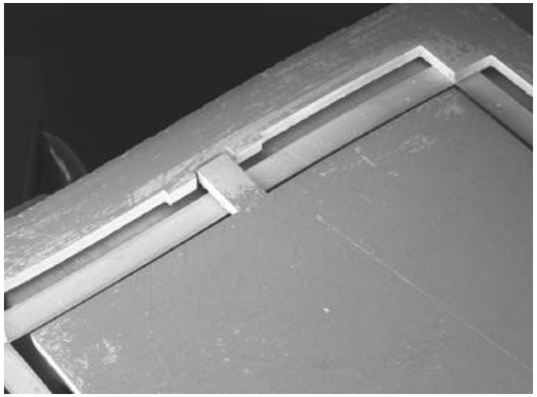
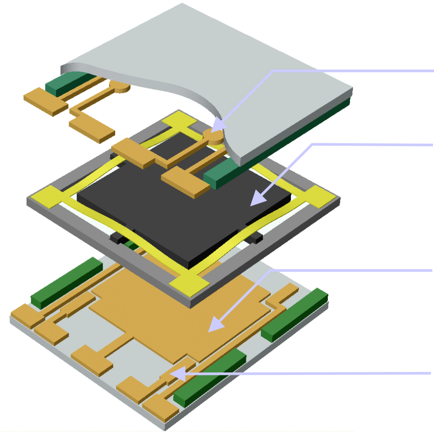
Early Non-Resonant Electrostatic Harvester





- Capacitor pre-charged when mass at bottom (max capacitance)
- Under sufficiently large frame acceleration, capacitor plates separate *at **constant charge***, work is done against electrostatic force

  $\Rightarrow$ stored electrostatic energy and plate voltage increase
- Charge transferred (at higher voltage) to external circuit when moving plate reaches top plate

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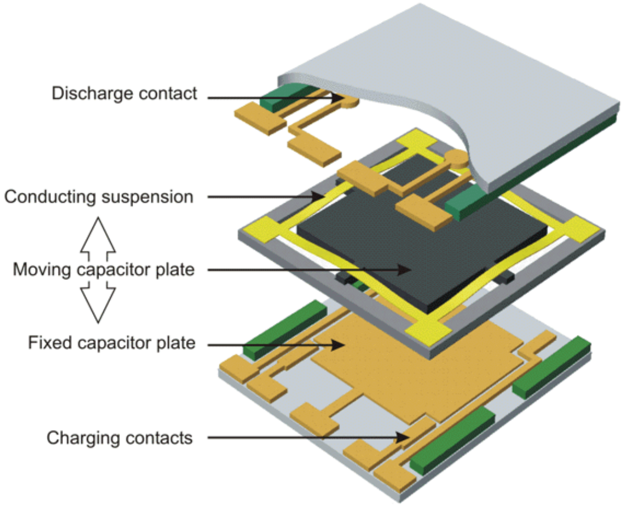
Miao P., Mitcheson P.D., Holmes A.S., Yeatman E.M., Green T.C., Stark B.H., "MEMS inertial power generators for biomedical applications", Microsystem Technologies, 12, (2006), 1079-1083.

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

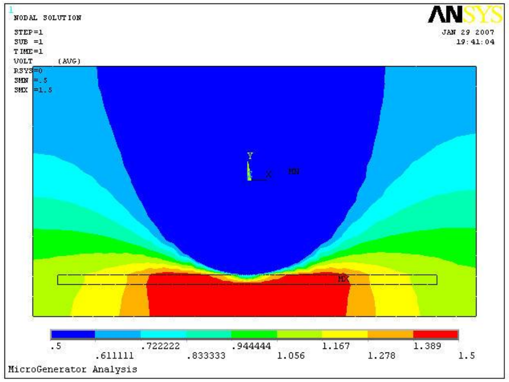


External Mass Electrostatic Harvester

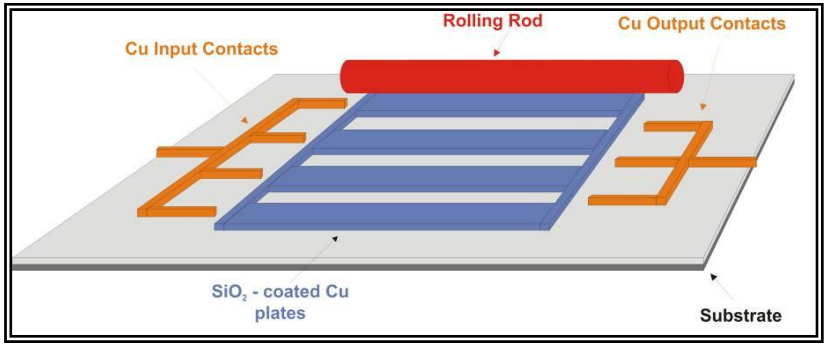
- Proof mass rolls on substrate
- Multiple charge-discharge cycles per transit
- No deep etching: fabrication simplicity
- Large mass and internal travel range

But:

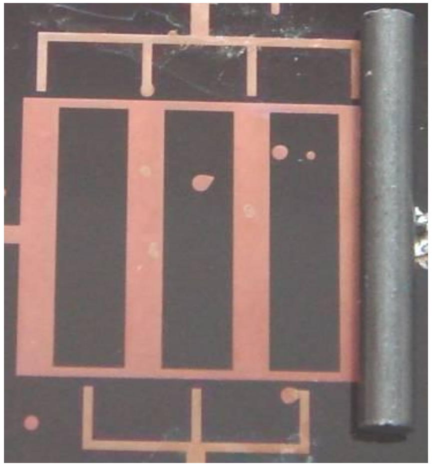
- Very low capacitances & capacitance ratios
- Thus, low power for given priming voltage



Electrostatic simulation



Schematic illustrating concept



Rolling mass on prototype device

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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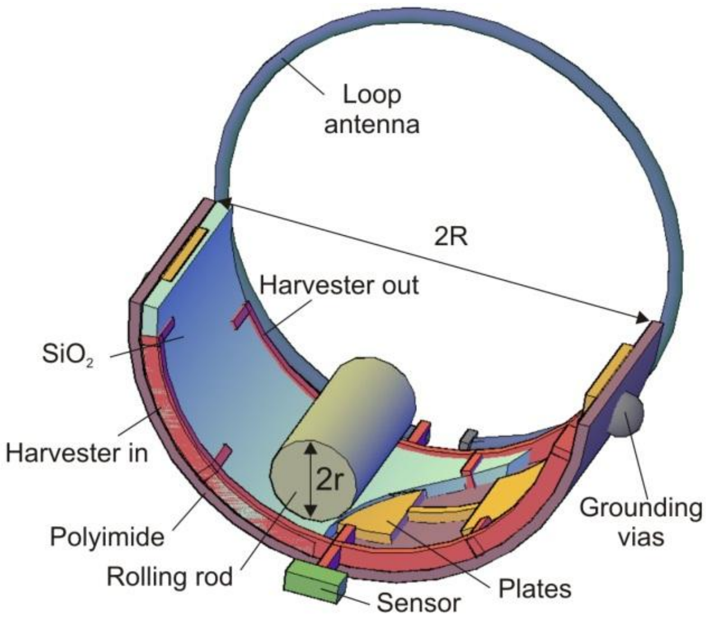
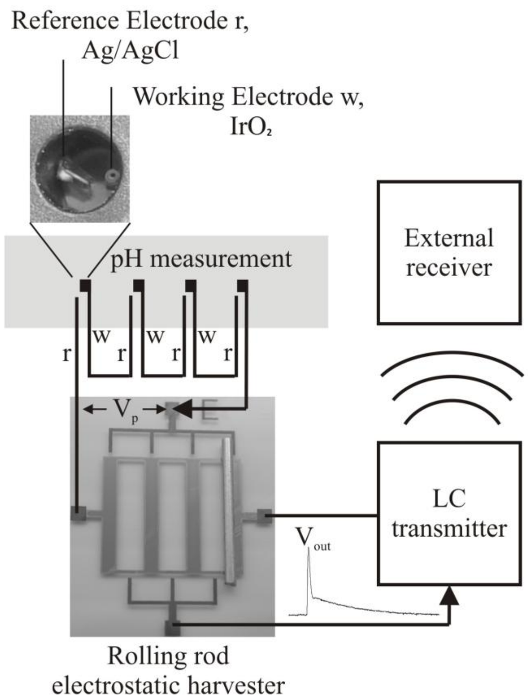
Rolling Element Harvester – Part 2

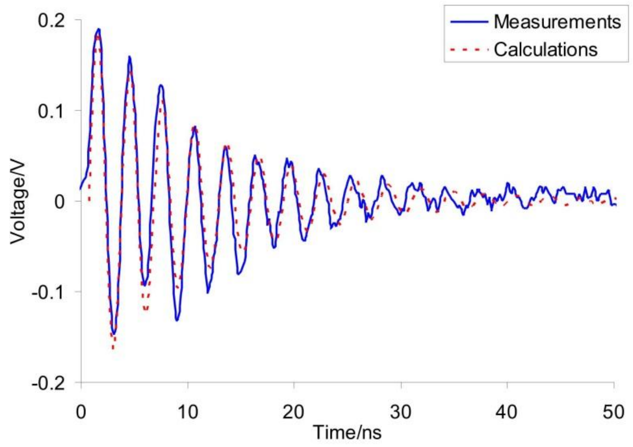




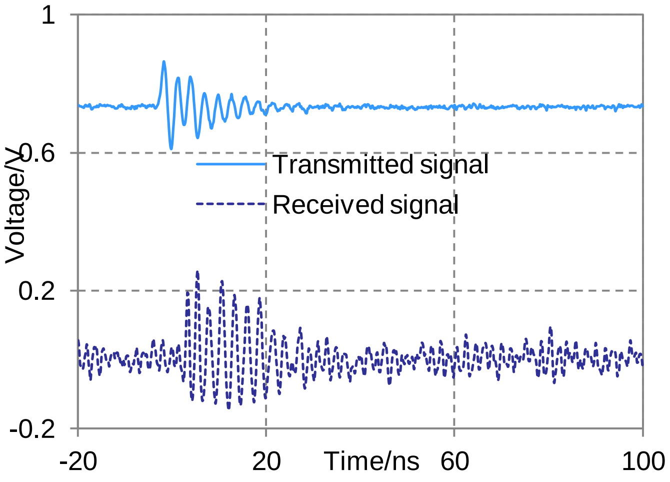
- Electrostatic harvester with rolling inertial element
- Output coupled directly to resonant transmitter
- Priming voltage provided by sensor; no processing electronics

He C., Kiziroglou M.E., Yates D.C., Yeatman E.M., “A MEMS self-powered sensor and RF transmission platform for WSN nodes”, IEEE Sensors Journal, 11(12), (2011), 3437-3445.

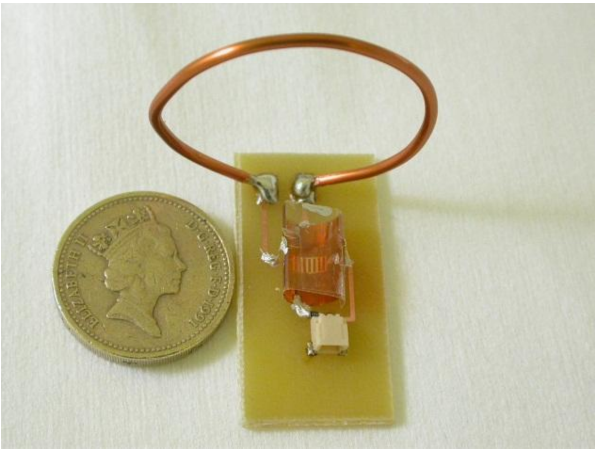
Rolling Element Harvester



Capacitively tapped measurement harvester discharging through the loop antenna, showing oscillation at 330 MHz.



Transmitted and received signals (with very different levels of amplification)



- Transmission over 1 m range successfullly demonstrated
- Minimum detected pulse energy ~42 pJ

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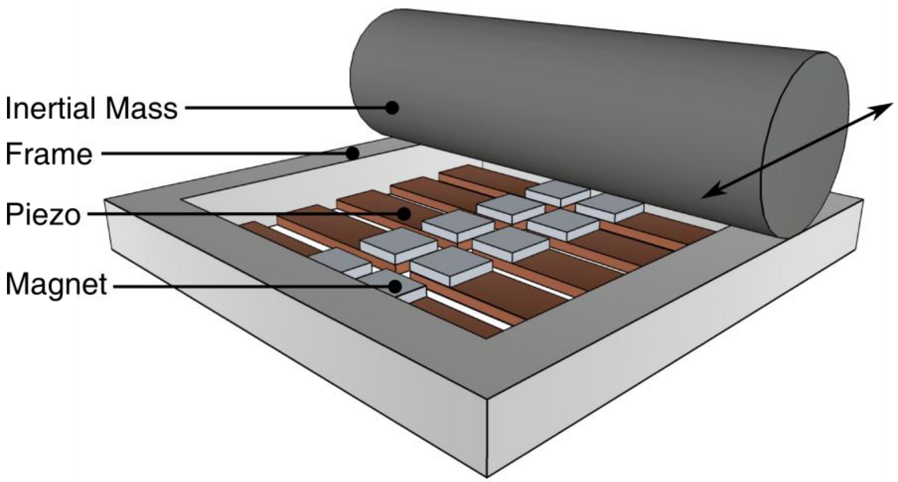
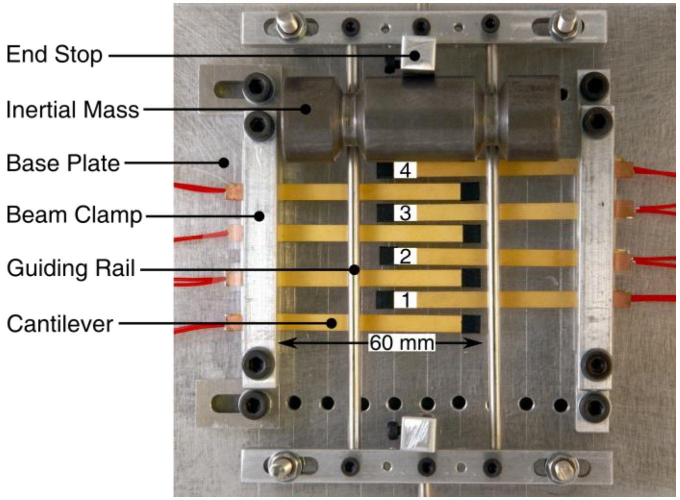
Impulse-Excited Rolling Element Harvester

- Alternative design of rolling element harvester, also designed for large amplitude, low frequency, non-harmonic excitation
- Distributed transduction via an array of piezoelectric beams
- Permanent magnets attached to beams snap to the proof mass as it passes, and then suddenly release leaving beams to resonate at natural freuency
- Frequency up-conversion improves electromechanical coupling





Pillatsch P., Yeatman E.M., Holmes A.S., “A scalable piezoelectric impulse-excited generator for random low frequency excitation”, Proc. IEEE MEMS 2012, Paris, 29 Jan – 2 Feb 2012, 1205-1208.

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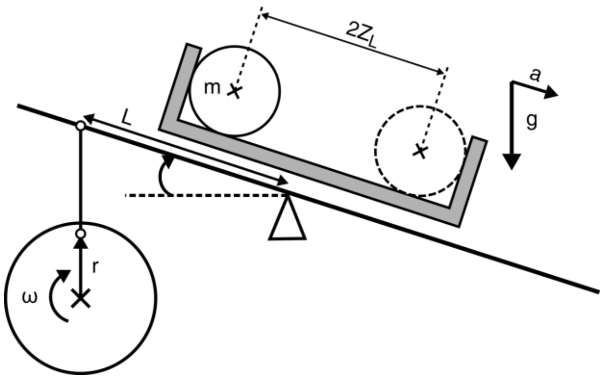
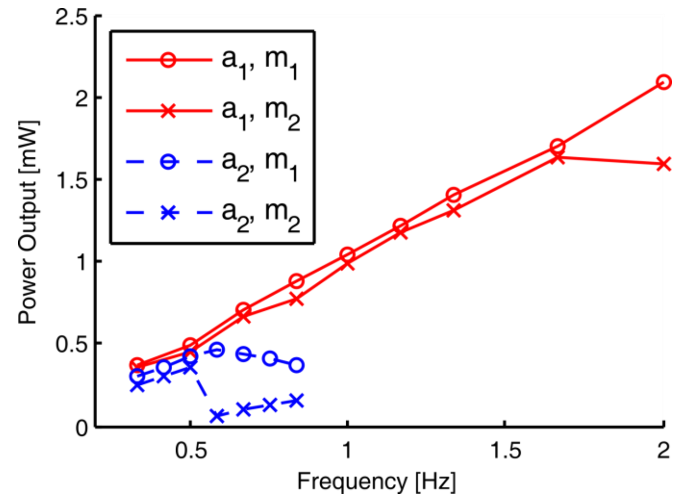
Impulse-Excited Rolling Element Harvester

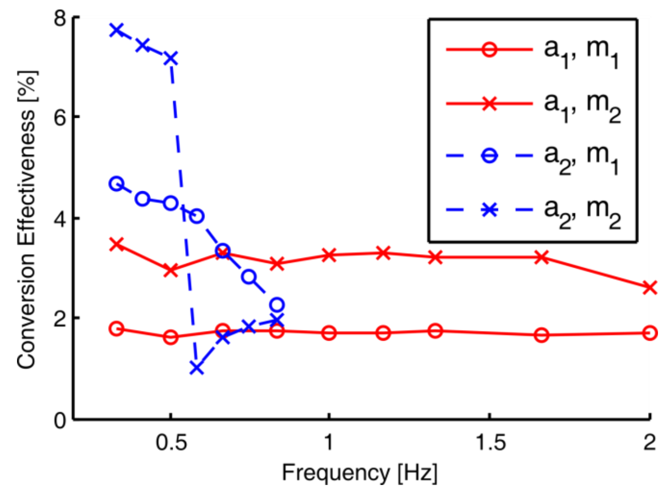


4 test configurations:

- $a_1 = 2.72$ 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 could be higher, but is quite reasonable for first design
- Power density of 4-13 μW/cm^3 for lighter proof mass
- Scalable design



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* (not rolling) proof mass:
limited motion range not inherent

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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Seiko Kinetic

- First introduced in 1986
- Electromagnetic generator powers a quartz movement
- High gear ratio necessary to achieve the required voltage, involves many interacting precision parts
- Storage capacitor in later models replaced by rechargeable battery
- Estimated power output around 5 μW

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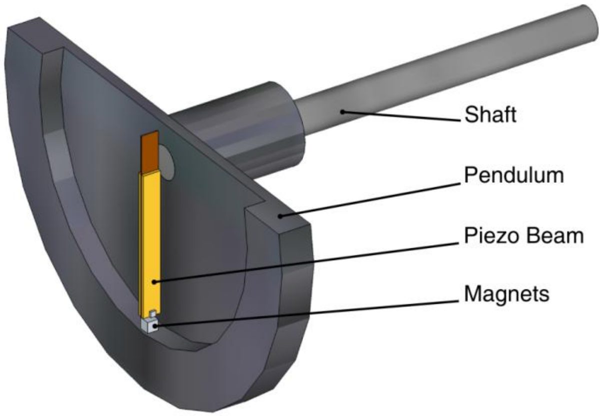
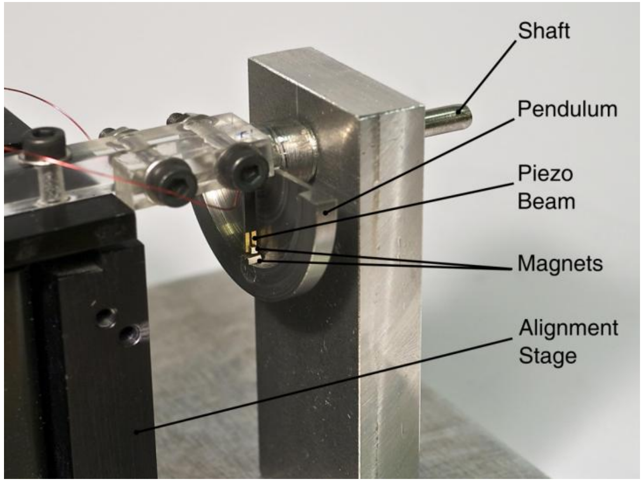
Impulse-Excited Rotating Element Harvester



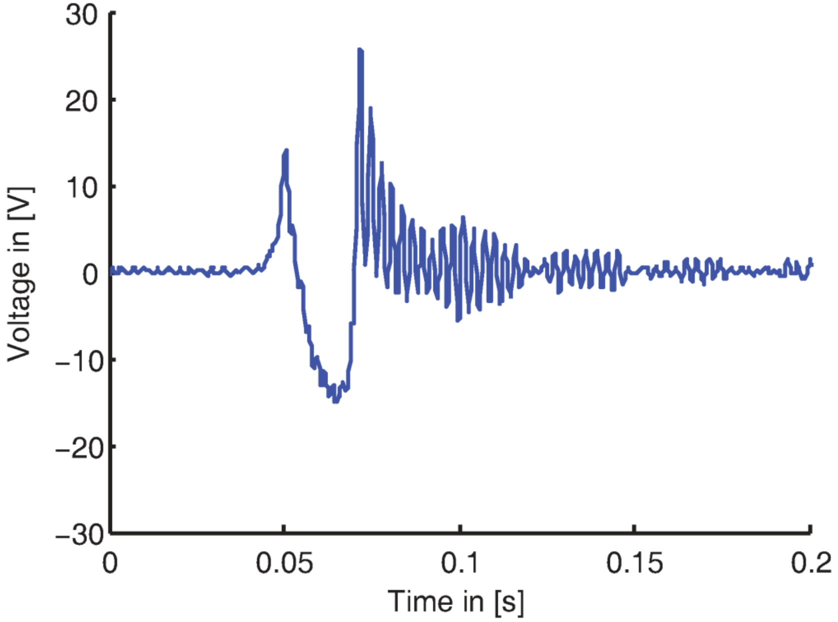


- Operation in any orientation
- Rotational and linear excitation
- No inherent displacement limit for the proof mass travel
- Compared to wristwatch generators:
  - No gears necessary
  - No mechanical contact due to magnetic coupling, good for long lifetime
  - Small number of parts, reduced cost
  - Convenient for miniaturization

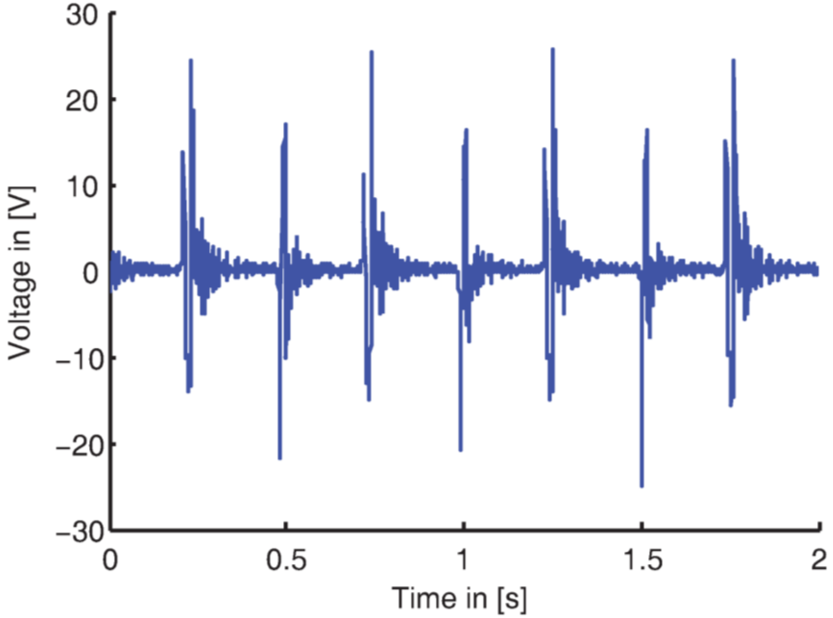
P. Pillatsch, E.M. Yeatman, A.S. Holmes, "Piezoelectric Rotational Energy Harvester for Body Sensors Using an Oscillating Mass", Proc. Body Sensor Networks, London, May 2012, pp. 6-10.

Experimental Results

Single actuation of the beam at 2 Hz and minimal gap h_0



Continuous actuation of the beam at 2 Hz and minimal gap h_0



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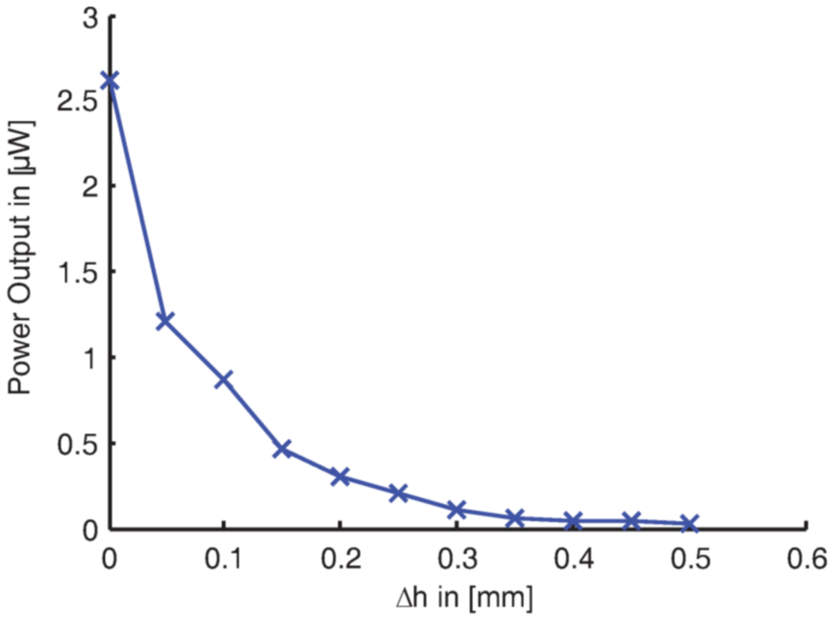
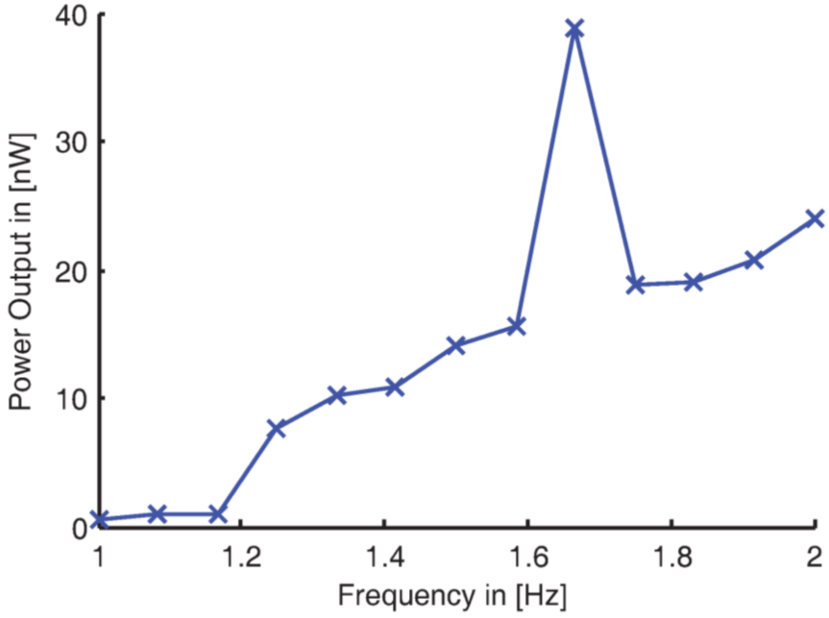
Experimental Results

Power output in relation to the relative gap Δh, measured at 2 Hz



Power output in relation to excitation frequency for a relative gap $\Delta h = 0.5\ mm$



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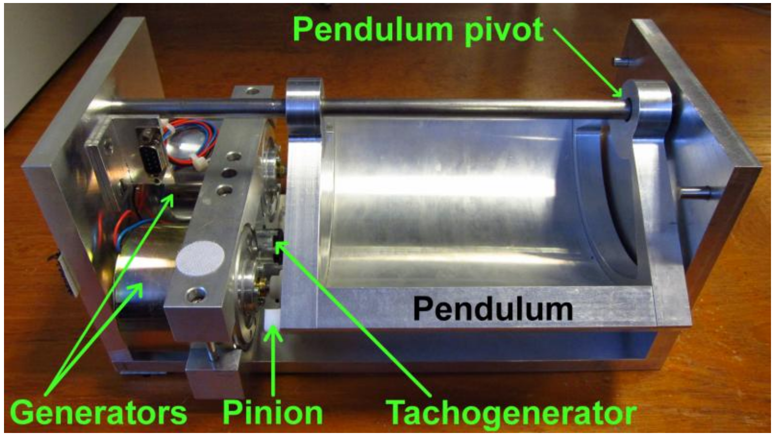
Marine Harvester

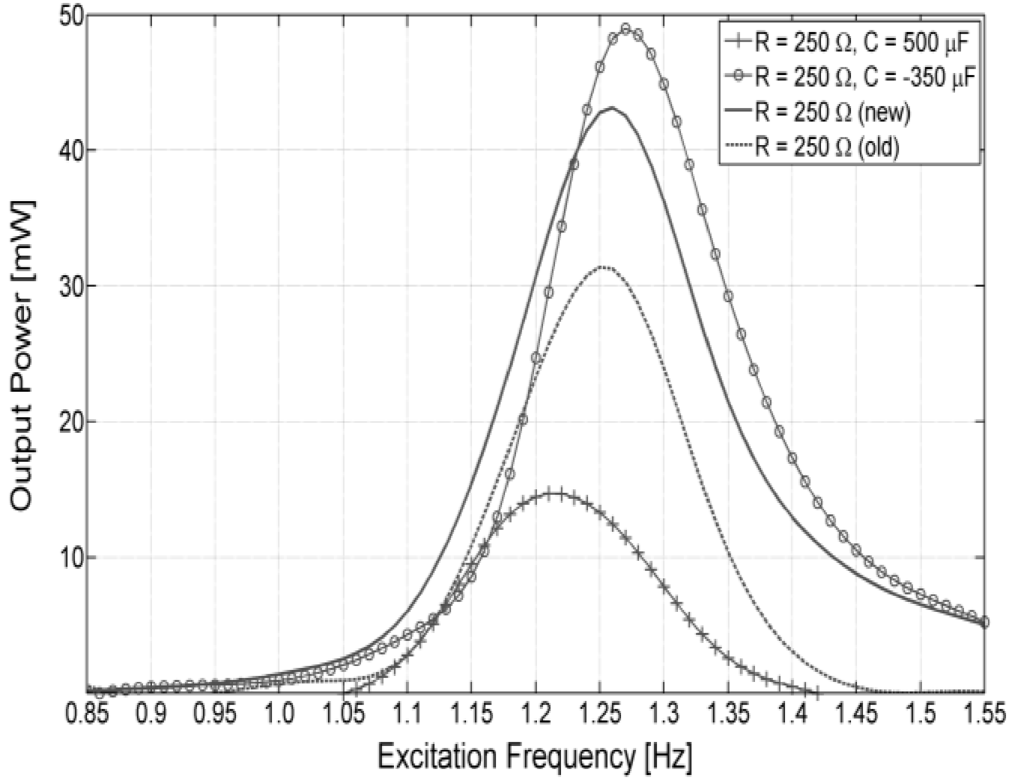
- Pendulum-type inertial harvester designed to provide back-up power for USV (un-manned surface vehicle) in case of power failure
- Developed as part of EU project (“Mobesens”) on large scale water quality monitoring



- Rocking of USV causes excitation of pendulum
- Electrical damping & transduction provided by a pair of DC generators
- Adaptive power electronic interface with tuning capability used to transfer power into rechargeable battery

Wong K.H., Toh T.T., Mitcheson P.D., Holmes A.S., “Tuning the resonant frequency and damping of an energy harvester using power electronics”, IEEE Trans. Circ. & Syst. - II, 58(2), (2011), 792-796.

Marine Harvester - Performance



- Both power optimisation and mechanical tuning achieved through synthesising complex electrical loads

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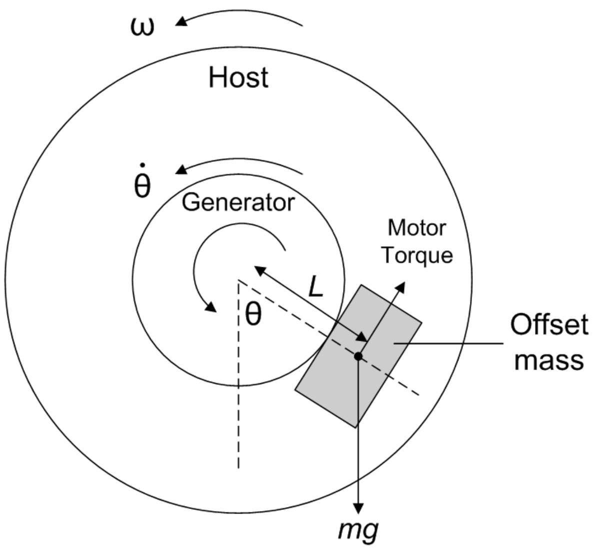
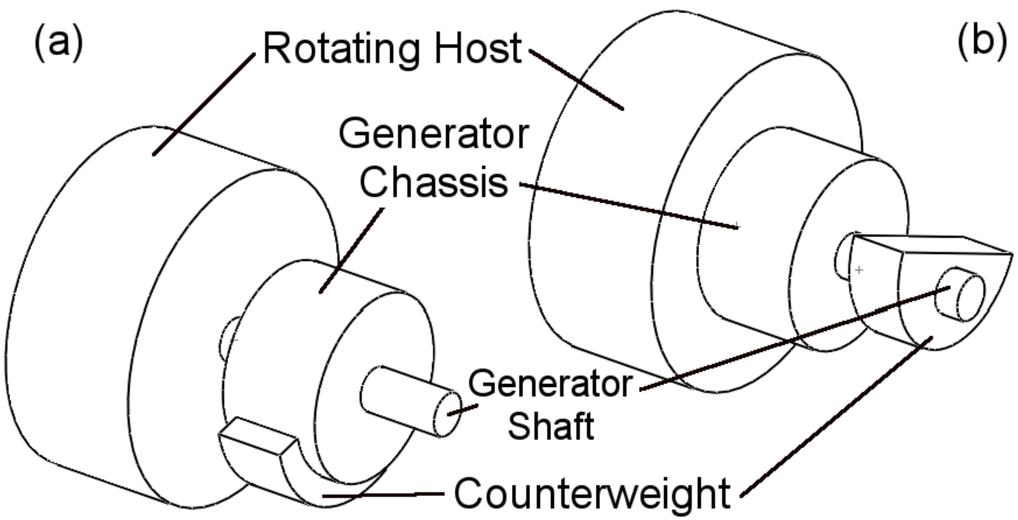
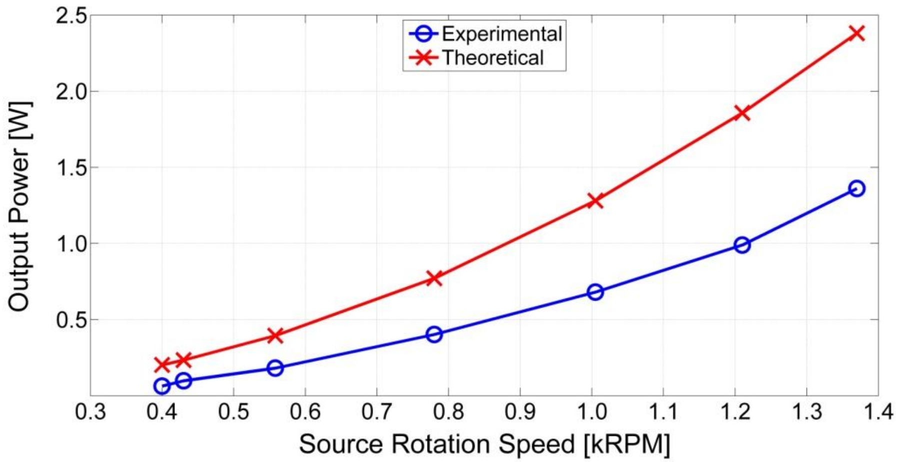
Harvester for *Continuously* Rotating Source

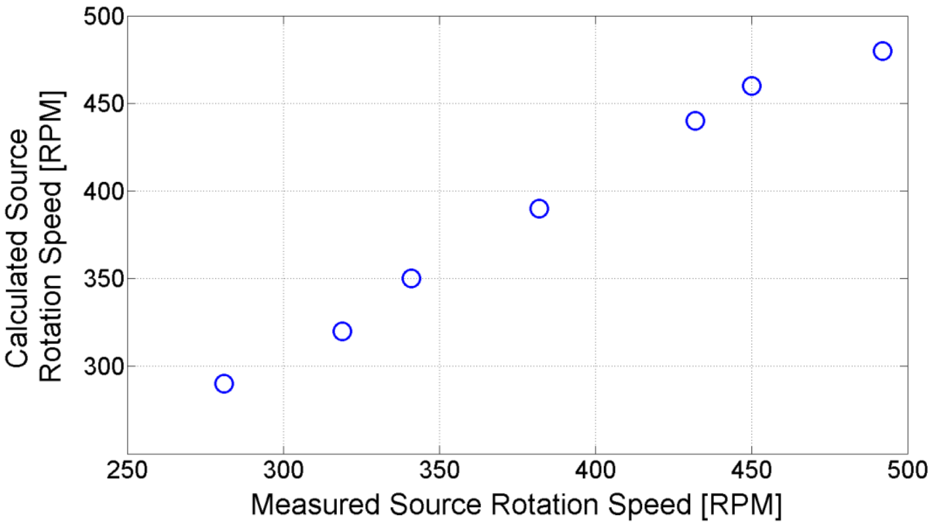




- Single point-of-attachment system for energy harvesting from rotation
- DC machine used for transduction
- Gravitational force on offset mass used to prevent rotation of one side of transducer (either casing or shaft)

Wireless Tachometer





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Overcoming Displacement Limit: Rotation Range

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

Freely rotating mass: can rotate > 360º but can only extract energy during 180º per half cycle (unless source motion > 360º !)

Any alternatives?

yes, *resonant* spinning mass

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

$$P_{\max} = \frac{mY_o Z_o \omega^3}{\pi} \qquad \text{vs.} \qquad P_{\max} = \frac{mR^2\theta_o^2\omega^3}{8}\sqrt{Q}$$

Result:

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

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?

Overcoming the Mass Limit

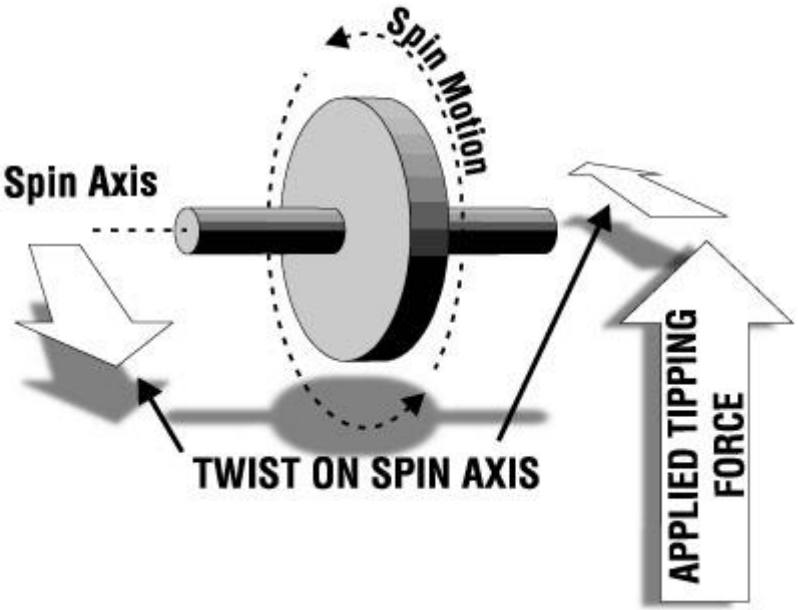
How else can rotating motion be used in inertial generation?

What about driving the rotation actively?

Gyroscopic power generation

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

torque $T = I\omega_s\omega_p$



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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

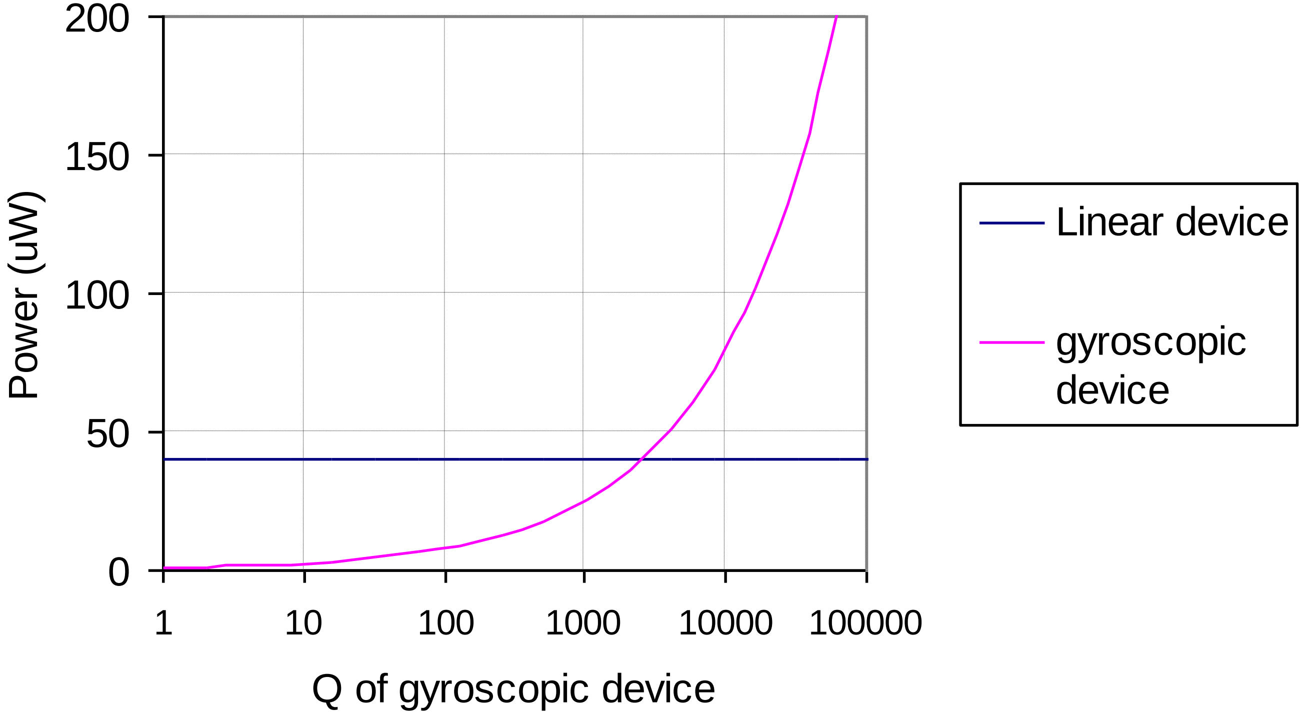
Gyroscopic power generation

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



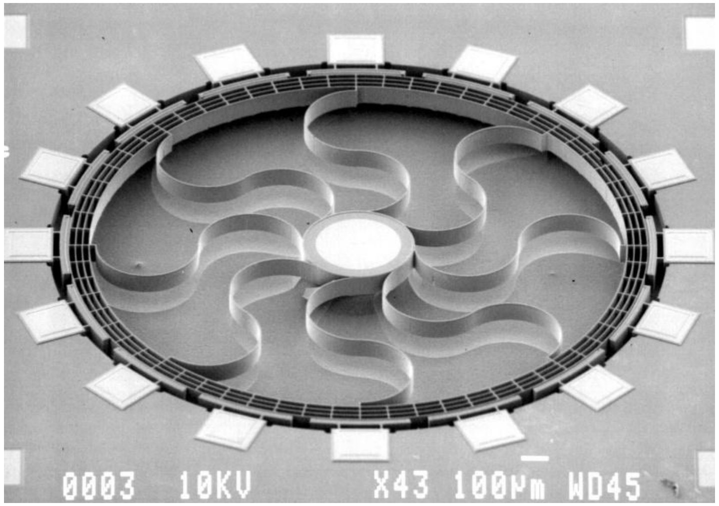
Gyroscopic power generation

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

Gyroscopic power generation

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

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



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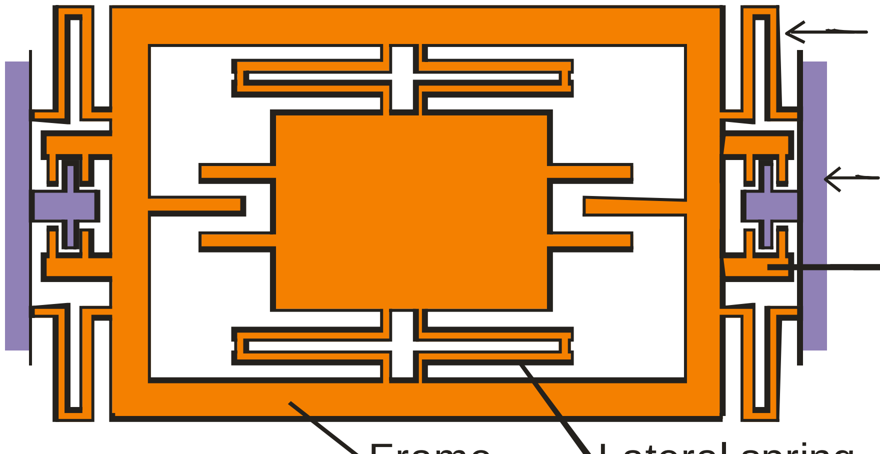
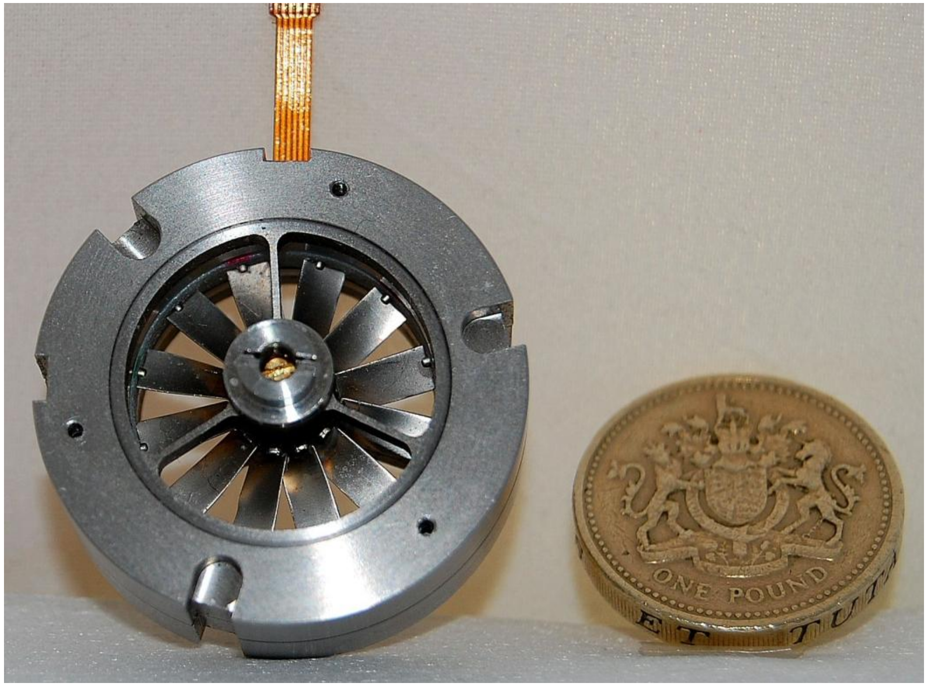
Gyroscopic power generation

- 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



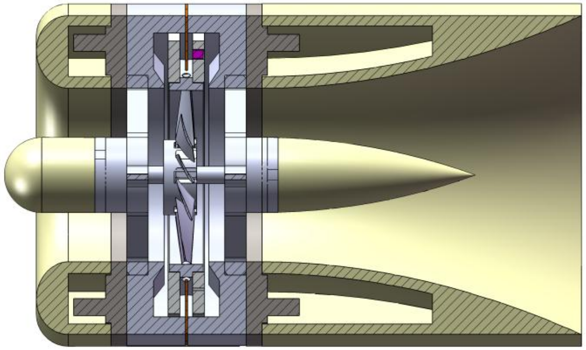
after Fedder et al

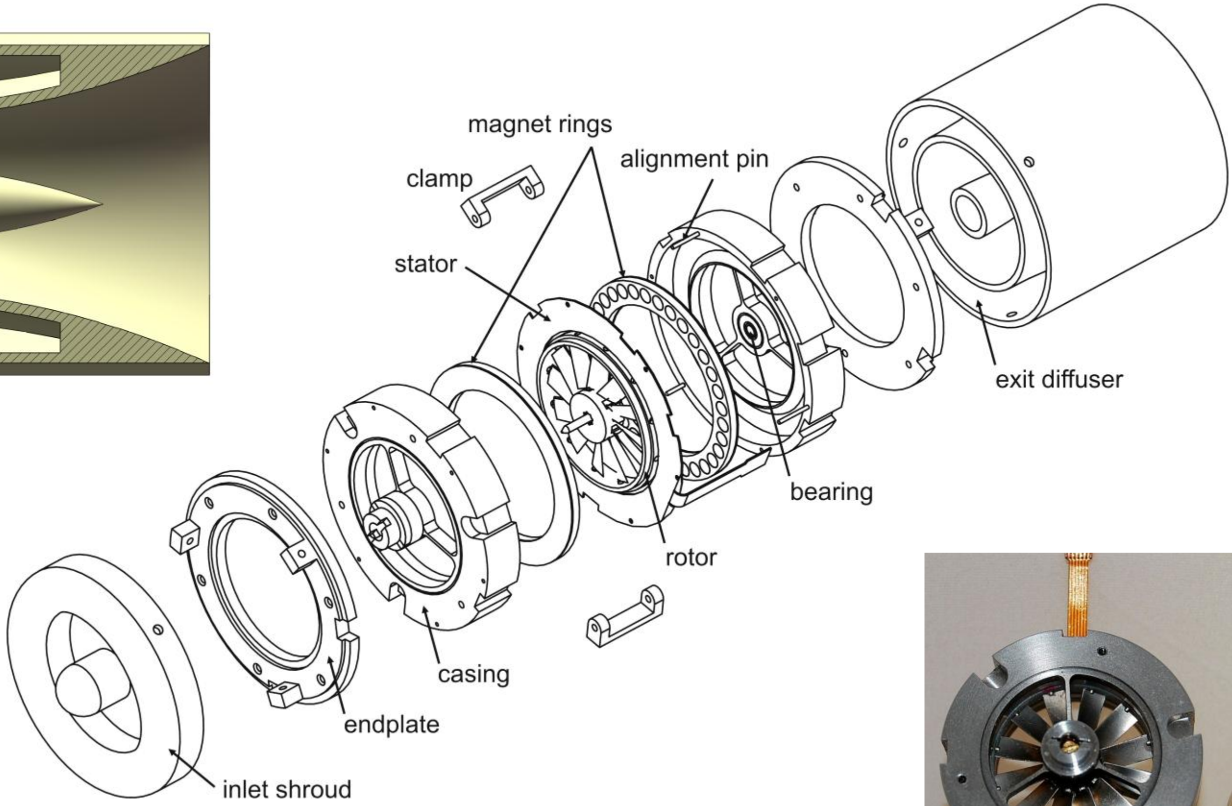
Flow-driven Harvesters

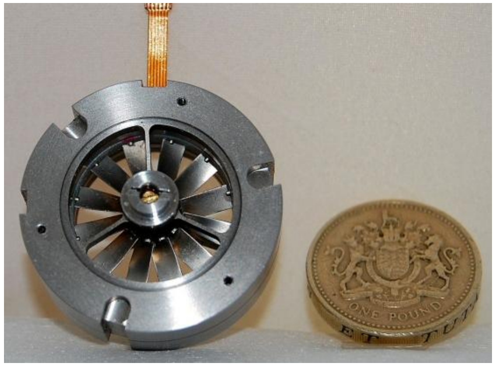


2-cm dia. Turbine developed at Imperial

- Ducted turbine with permanent magnet generator integrated into shroud
- Aimed at duct/pipeline monitoring
- 3.2 cm diameter shroud (1% obstruction in 1 ft diameter duct)







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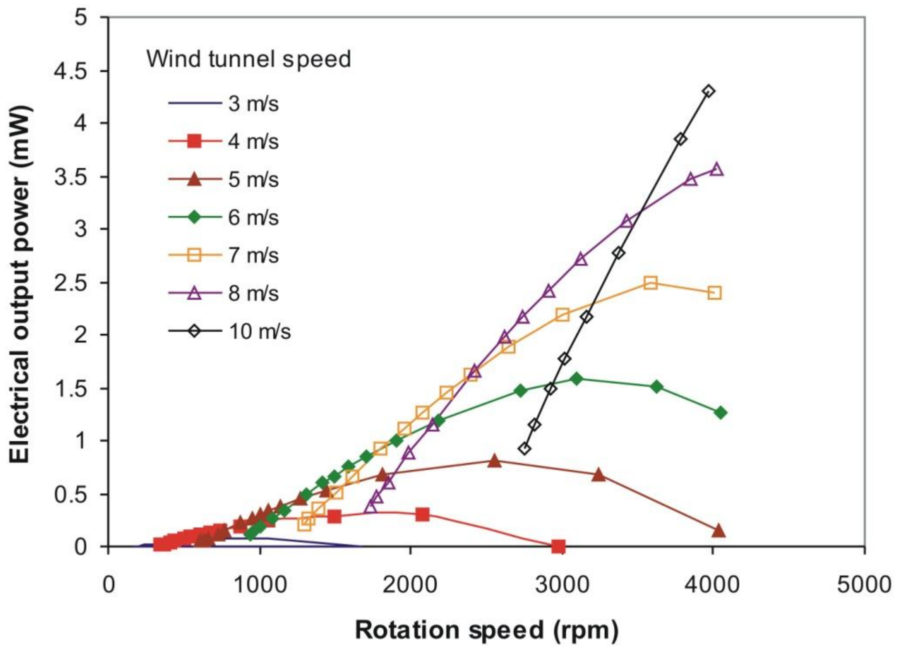
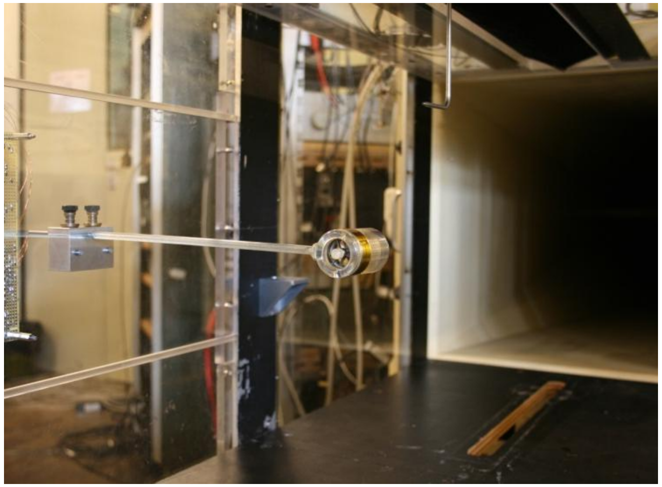
Performance

- Performance testing carried out in 18” x 18” wind tunnel to obtain performance curves at different wind tunnel speeds
- Separate spin-down tests under vacuum used to establish bearing losses





D.A. Howey, A Bansal and A.S. Holmes, “Design and performance of a centimetre-scale shrouded wind turbine for energy harvesting”, Smart Mater. Struct. 20(8), 2011, 085021.

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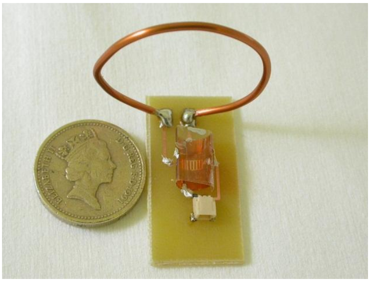

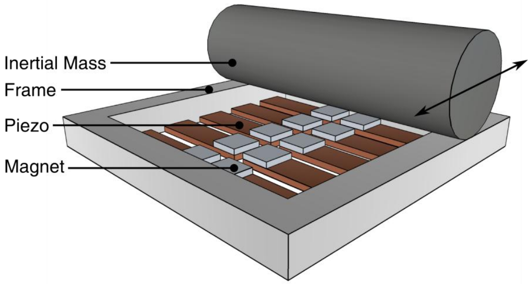

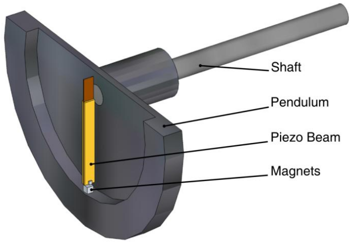

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