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London

Vibration Energy Harvesting

Basics

Paul D. Mitcheson

NIPS workshop 2014

Overview

- Motivation
- EH Overview
- Transducers Overview
- Fundamental Analysis and Optimisation
- System Modelling and Simulation Approaches
- Transducer and Power interface Requirements
- Bringing it together - piezoelectric Example
- Conclusions

These systems fundamentally have strong coupling between electrical and mechanical parts – hence even a basic overview must consider the electronic load

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Imperial - history

1851–1890 Constituent Colleges formed, Prince Albert and the Great Exhibition

1907 Imperial College founded by merger of:

- City and Guilds College
- Royal College of Science
- Royal School of Mines

1988-2000 Mergers with:

- St Mary's Hospital Medical School
- National Heart & Lung Institute
- Charing Cross/Westminster and Royal Postgraduate Medical Schools
- Kennedy Institute

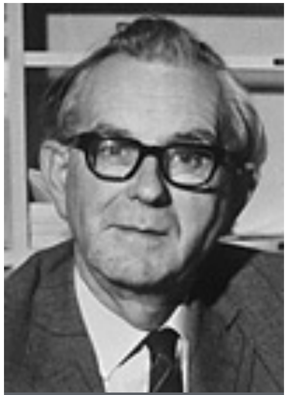
2007 Left the University of London to become an independent university

Past achievements

14 Nobel Prize Winners associated with Imperial College

Alexander
Fleming:
Penicillin

Denis
Gabor:
Holography



Rodney
Porter:
Stucture of Antibodies

Andrew
Huxley:
Nerve Impulses

Abdus
Salam:
Theoretical Physics

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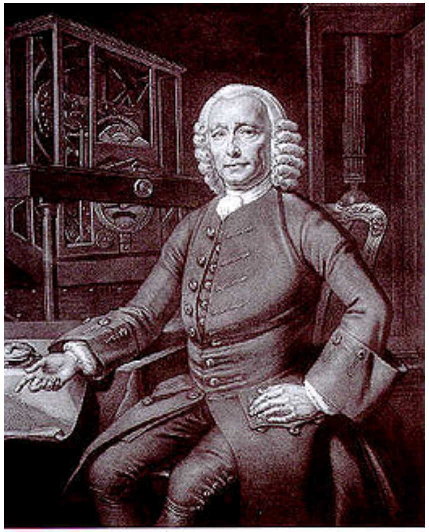
Electrical and Electronic Engineering Dept
11 story building – spot the cleanrooms…

But I'm not from London Originally

- When you ask an Italian born in Rome what nationality he is, he will say he is Roman, not Italian.
- People from Yorkshire are similar…
- They are also suborn and talk with funny accents (I have been away for too long..)

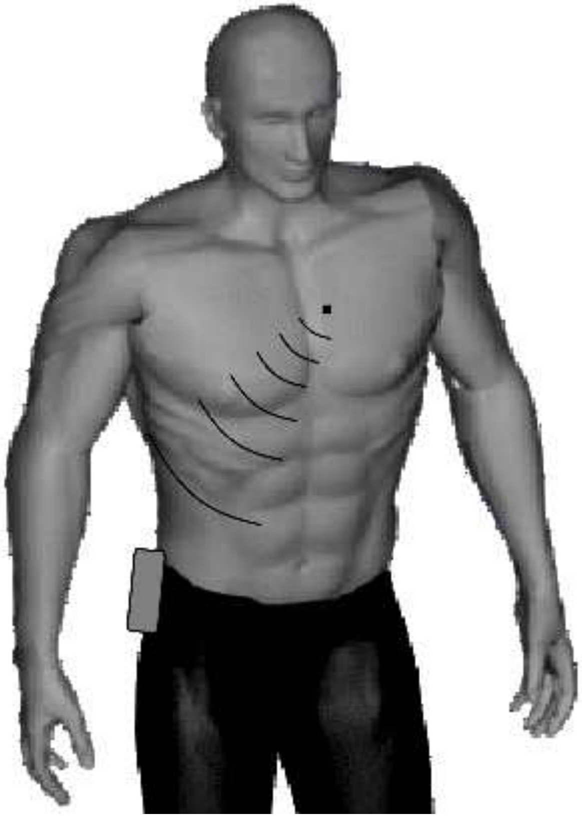
What is Yorkshire Famous for?



EH Overview

Energy Harvesting – Original Motivations

- Energy harvesting – replacement of finite power sources in portable devices by converting ambient energy into electricity through the use of an energy harvester
- The field started to emerge in about 2000
- Needs knowledge on devices, physics and electronics
- A very small number of people had looked at some type of harvesting from high frequency vibration
- My original motivation was to look at human body powering of implantable sensors



Orders of Magnitude of Power

World electrical generation capacity	4 terawatts
Power station	1 gigawatt
House	10 kilowatts
Person, lightbulb	100 watts
Laptop, heart	10 watts
Cellphone power usage	1 watt
Wristwatch, sensor node	1 microwatt
Received cellphone signal	1 nanowatt

Sensor nodes are receiving a lot of interest – but the constraints on volume and power are significant and we must push design to the limit

Sources for Harvesting

Energy Source	Conversion Mechanism
Light Ambient light, such as sunlight	**Solar Cells**
Thermal Temperature gradients	**Thermoelectric or Heat Engine**
Magnetic and Electro-magnetic Electro-magnetic waves	**Magnetic induction** (induction loop) **Antennas**
Kinetic Volume flow (liquids or gases) Movement and vibration	**Magnetic** (induction) **Piezoelectric** **Electrostatic**

Why choose Kinetic/Vibration Devices?

Original reasons:

- Thermal gradients are small at small sizes on body
- In most places (unless close to a base station) RF energy is quite limited
- Solar is no good for implanting into the body
- So movement seemed a logical choice
- Open research with lots of interesting questions

Seiko stopped production of the thermic watch but continue the kinetic device

Motion Energy Harvesting

- Direct force devices (like most electrical generators)

- Inertial devices (most energy harvesters are of this form)

This is a very important distinction…

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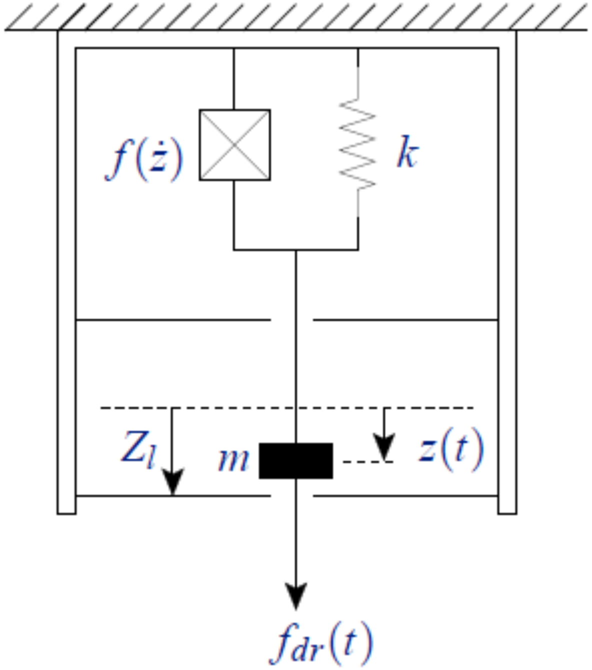
Direct Force Device



- A force applied to a transducer
- Energy generated is force-distance integral
- Transducer could be piezoelectric, electrostatic or electromagnetic
- System dynamics probably dominated by driving force, *fdr(t)*
- If driving force is large enough, then make the damping as big as possible

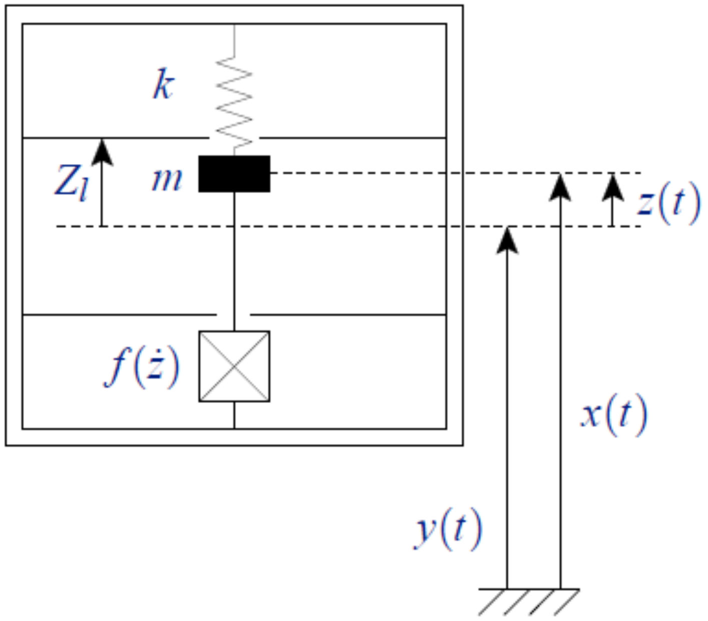
Direct Force Generators

Heel strike generator: Paradiso et al, MIT

East Japan Railway Co.

- Energy harvesting ticket gates

Inertial Generators



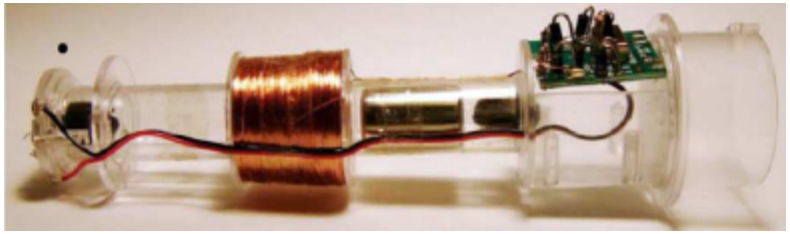
We are going to spend a lot of time with this "mass in a box" model…

Simple principle:

- Shake the box
- Mass moves relative to the frame
- Transducer damps the motion and outputs electrical power
- Aim is to maximise power dissipation (conversion) in the damper (again, force distance integral)
- Damper can be electromagnetic, electrostatic or piezoelectric
- Can't just make damping force arbitrarily large as this limits mass travel

Inertial Generator - Large Examples

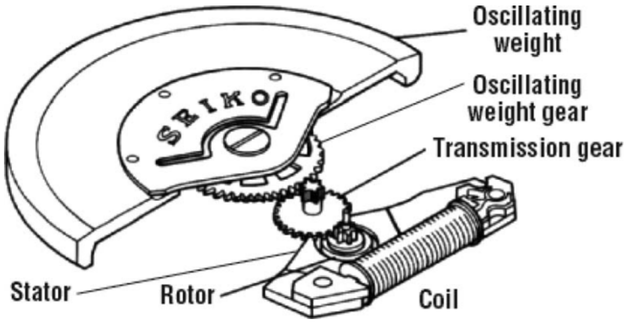
Larry Rome, Penn State



Harvesting torch

Inertial Devices – smaller examples

- Capture energy from the environment and convert to an electrical form



Seiko kinetic watch generator

•PMG17 from Perpetuum Ltd

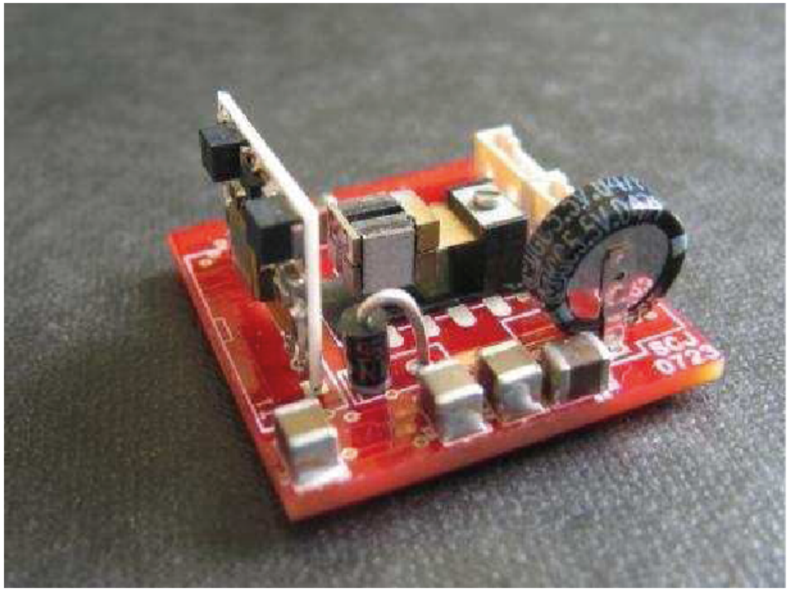
•Resonant generator tuned to 100 or 120 Hz

•55 mm diameter x 55 mm length

•4.5 mW output power (rectified DC) at 0.1g acceleration

Electromagnetic Transducers - example

- Vibes Generator (Steve Beeby and others)



- 2800 turns on coil
- 50 Hz and 60 mg operation
- Output voltage around 700 mV RMS
- Output power 55 μW

Self-powered sensor and transmitter demonstrated

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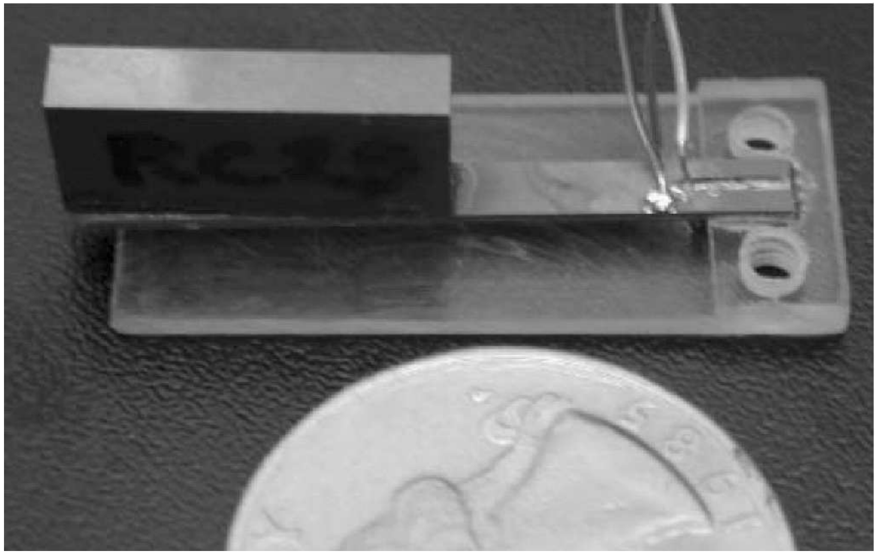
Piezoelectric Transducers - example

- UC Berkeley Generator (Shad Roundy and others)



- 120 Hz and 60 mg operation
- Input amplitude 4.4 μm
- Output power 116 μW

Self-powered sensor and transmitter
demonstrated from similar device

Electrostatic Transducers - example

- MIT Generator (Mur Miranda and others)

- Referred to as comb drive in MEMS community
- Constant V sliding approach
- Simulations show an expected 8 μW from a 2.5 kHz input

Summary of Overview

- Large scale power generation uses direct-force type generation
- This is not suitable for harvesters because applications usually limit the generator to one attachment point
- This (as well as practical constraints) places fundamental limits on the power density of these systems
- Kinetic harvesters have been seen in some practical scenarios and are a still growing research topic

Transducers Overview

Performance limits of the three MEMS inertial energy generator transduction types

PD Mitcheson, EK Reilly, T Toh, PK Wright, EM Yeatman

Journal of Micromechanics and Microengineering 17 (9), S211

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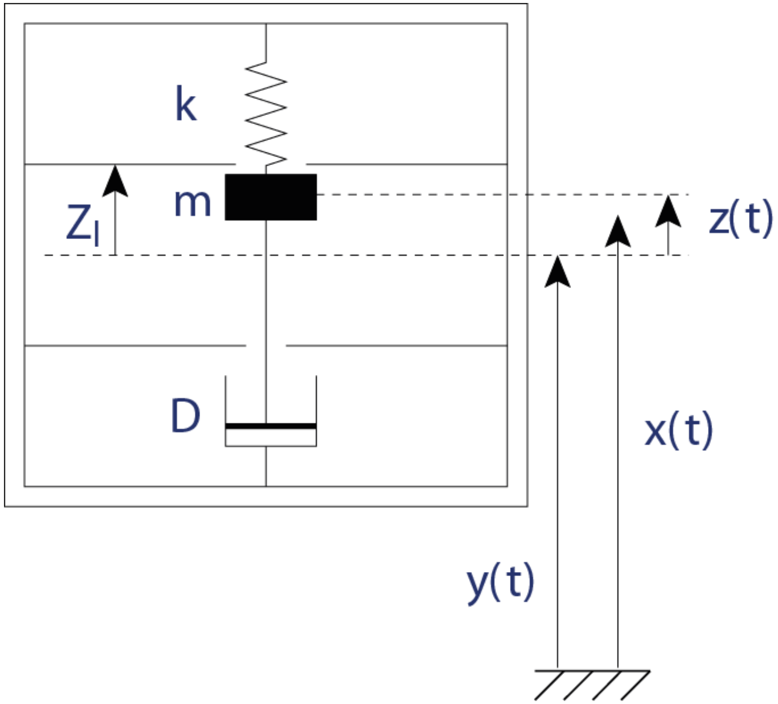
Transducers

- There are essentially two phenomena that can be used to convert (relative) motion into electrical energy (or vice versa)
- Electromagnetic/electrodynamic force
- Normally used in macro scale devices (eg motors, power stations…)
- Electrostatic force
- Often found in MEMS

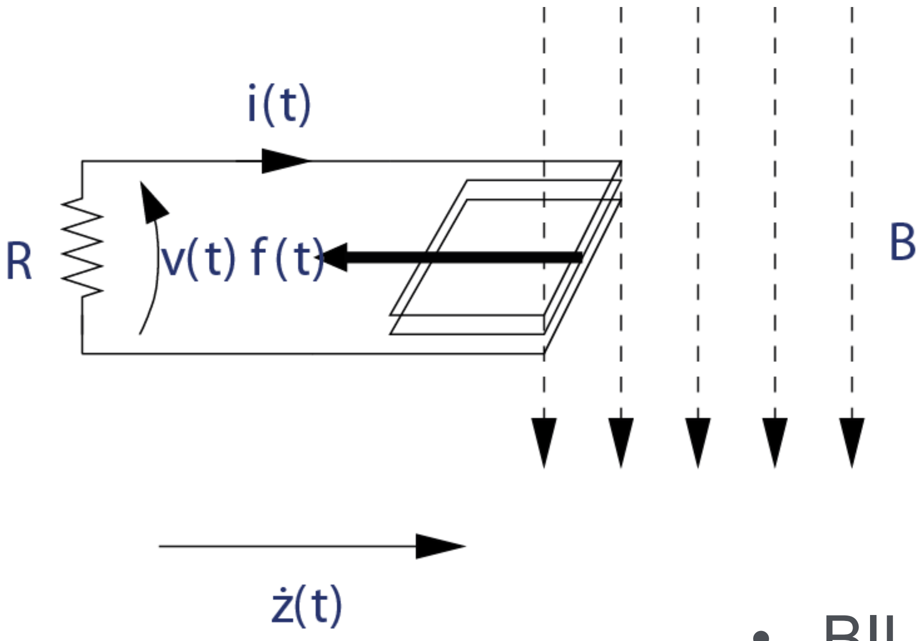
- The electromagnetic force can be implemented
  - with a coil and magnet
- The electrostatic force can be implemented in several ways
  - Moving plate capacitor
    - (dis)charged by an external circuit
    - Primed using an electret
  - A piezoelectric material

Which is Best and Why?

- Surprisingly hard question to answer!
- Back to the mass in a box
- What value of damper should we choose to maximise power generation?
- What does this depend on?
- What should the damper characteristic be? Linear, non-linear?
- What are the practical limits?
- How difficult/efficient is each damper when connected to a circuit?



Electromagnetic Transducers – basic theory



- Change of flux induces a voltage on the coil
- Current flows
- Lorentz force acts as *linear* damper

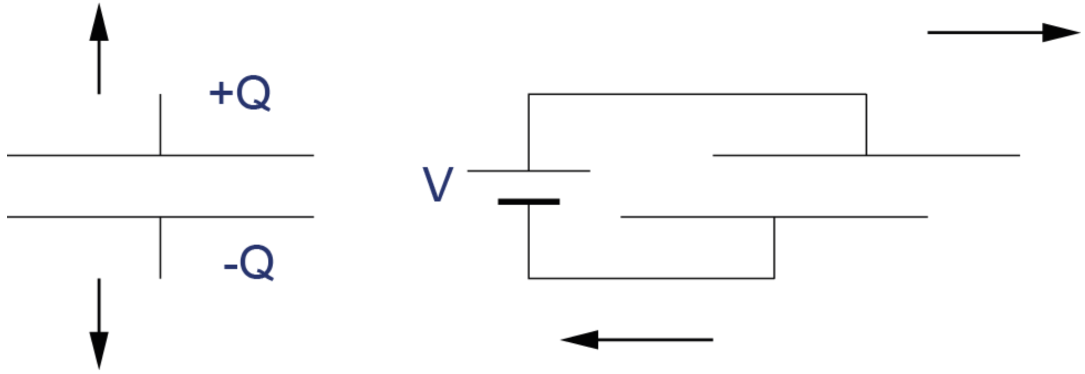
$$F(t) = \frac{(NBl)^2 \dot{z}(t)}{R}$$

- BIL product from generated emf
- *N* is number of coil turns and *l* is active coil length

If we ignore coil inductance force is proportional to velocity

Electrostatic Transducers - options

- Easy to achieve a Coulomb force, and two methods available:
  - Changing separation of plates in constant charge and constant overlap
  - Changing overlap of plates at constant voltage and constant separation



Energy generated is Force × Distance

Electrostatic Transducers - equations

- Changing separation at constant Q:

$$F = \frac{1}{2}\frac{Q^2}{\varepsilon A}$$

A is plate area

- Changing overlap at constant V:

$$F = \frac{1}{2}\frac{V^2 \varepsilon w}{d}$$

w is plate width and *d* the separation

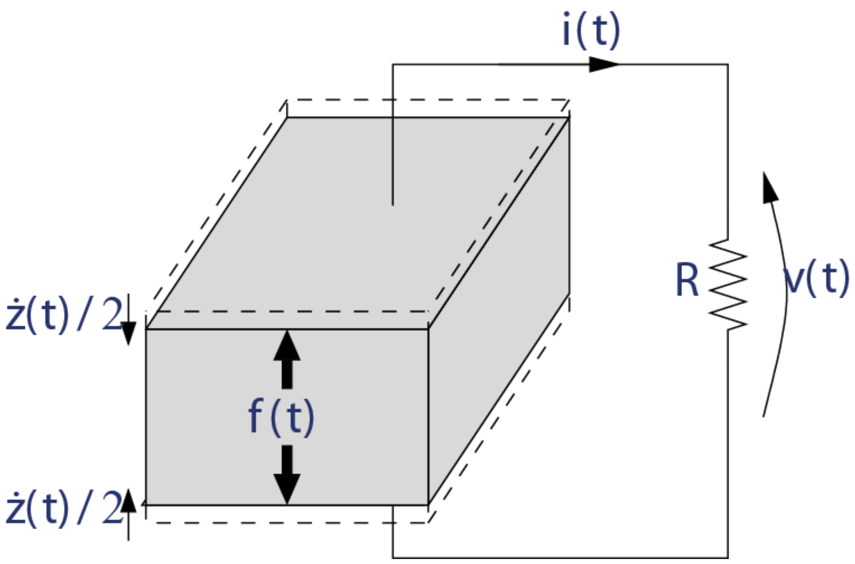
- In both cases F is constant (Coulomb)

Constant Q Operation

- Capacitor must be precharged at C_{max} to optimal voltage (to give optimal damping)
- Plates separate to give C_{min} under constant Q
- Voltage on plates rises
- Energy generated is:

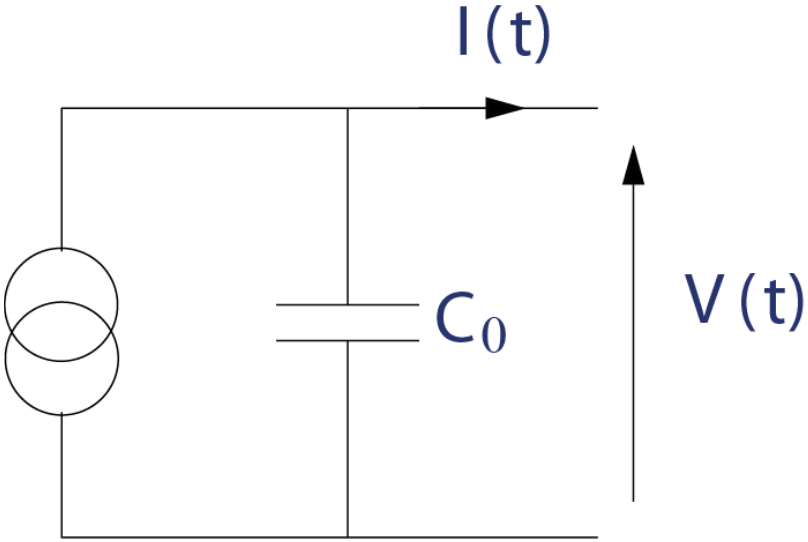
$$E = \frac{1}{2}Q^2\left(\frac{1}{C_{\min}} - \frac{1}{C_{\max}}\right)$$

Piezoelectric Transducers - Principle



- When the piezoelectric is strained, a current is generated
- Some of the charge ends up on the internal capacitance
- Some can flow in an external load

Piezoelectric Transducers - equations



$$F(t) = K_{PE} z(t) + \alpha V(t)$$

$$I(t) = \alpha \dot{z}(t) - C_0 \dot{V}(t)$$

F(*t*) is the force on the transducer, C_0 the internal piezo capacitance, *V*(*t*) the terminal voltage, *z*(*t*) the displacement and α and K_{PE} *are* material constants

Piezoelectric Transducers - behaviour

- For a resistive load the transducer force is:

$$F(s) = Z(s)\left(K_{PE} + \frac{s\alpha^2 R}{1 + sC_0 R} \right)$$

- This can be written as a constant valued spring constant (K_{PE}) plus a frequency dependent high pass term:

$$F_{\mathrm{HP}}(\mathrm{j}\omega) = Z(\mathrm{j}\omega)\left(\frac{\mathrm{j}\omega\alpha^2 R}{1 + (\omega C_0 R)^2} + \frac{\omega^2\alpha^2 C_0 R^2}{1 + (\omega C_0 R)^2} \right)$$

damper *spring*

Piezoelectric Transducer - explained

- We can therefore think of the piezoelectric transducer with a resistive load as presenting a spring constant and a damping term
- Both of these are frequency sensitive
- Nonetheless, at a given frequency, the damping can be calculated and the system behaves linearly (i.e. generates no harmonics)
- Damping is maximised (*dF/dR*=0) when:

$$R = \frac{1}{\omega C_0}$$

Practical Aspects

- There are limits on the maximum forces that can be developed for these transducers
    - There are maximum voltage limits on the piezoelectric and electrostatic devices due to either breakdown of the dielectric medium, or the attached circuit components
    - There are limits on the current that can flow in the electromagnetic transducer due to coil resistance
    - There are limits on damping in the piezoelectic device due to the output capacitance (i.e. not all the displaced charge can be forced through a chosen load)
- The circuit requirements have a significant effect on system performance

Summary of Transducers

- 2 phenonena
  - Electromagneitc or electrodynamic
  - Electrostatic

- 3 common implementations
  - Magnetc and coil
  - Moving plate capacitor
  - Piezoelectric

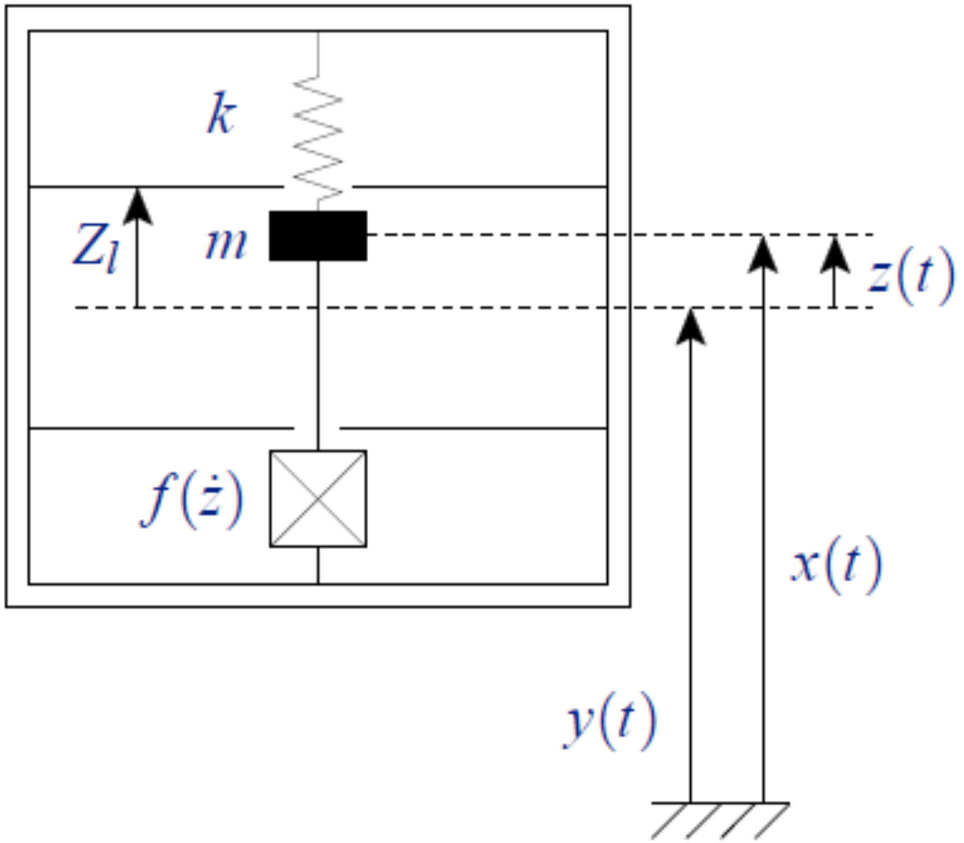
- Each has a different velocity-force characteristic (which also depends on the connected circuit element

- Practical constraints on each type limit the magnitude of the damping

Fundamental Analysis and Optimisation

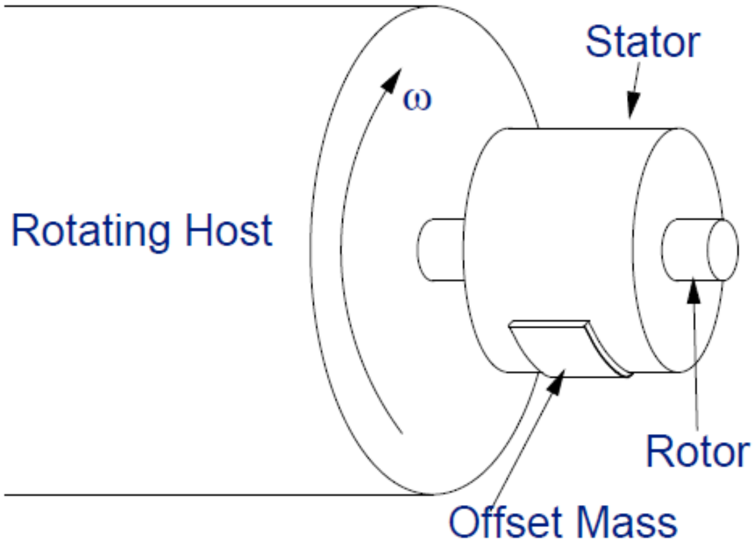
Architectures for vibration-driven micropower generators
PD Mitcheson, TC Green, EM Yeatman, AS Holmes
Microelectromechanical Systems, Journal of 13 (3), 429-440

Optimise the mass in a box model...



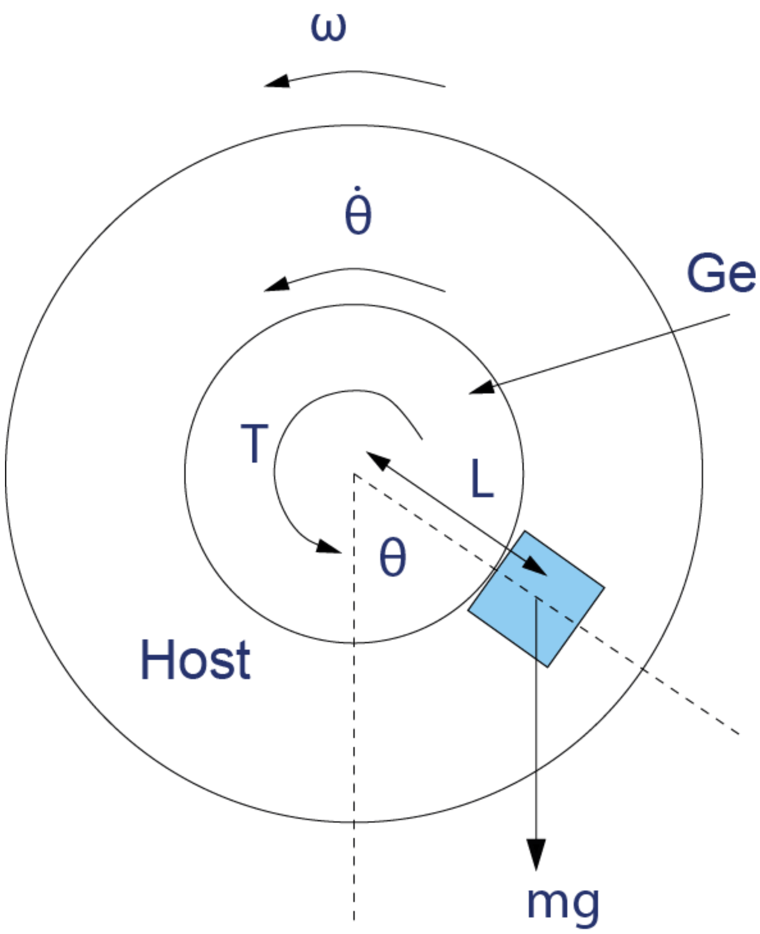
How do we maximise the power dissipated in the damper?

Simple Example as a Warm-Up!



- Host structure rotates
- Gravitational torque on offset mass holds stator in place
- Power generated is produced of force and angular velocity

Rotational Micro-Generators – Formula



- Power is simply Torque × angular velocity

$$P = mgL\sin\theta$$

And to optimise…

Rotational Generator Optimised Power

- So the limit on power generation in the rotational case is:

$$P_{\max} = \omega mgL$$

- Requires motor torque to be held at:

$$T_{opt} = mgL$$

- Overestimates power at low speeds with electromagnetic implementation
- This is because winding resistance ignored in basic model

Design Choices

- We have seen there are 3 ways of implementing the damper. What are their characteristics?
  - Electromagnetic - the force will likely be proportional to velocity.
  - Piezoelectric - force could be proportional to velocity
  - Electrostatic - Coulomb force (like sliding friction)
- And we have other design choices to make for our mass in a box
  - Resonant or non-resonant?
  - Aspect ratio, materials, etc

Inertial Generator Architectures

Architecture	*Damper*	*Spring*	*Damping Force*
Resonant	El. Mag/Piezo	$k = m\omega_n^2$	$f(t) = \dot{z} \times D$
Resonant	Electrostatic	$k = m\omega_n^2$	$\mathrm{f}(\mathrm{t}) = -\mathrm{sgn}(\dot{\mathrm{z}}) \times \mathrm{F}$
Non-resonant	El. Mag/Piezo	$k = 0$	$f(t) = \dot{z} \times D$
Non-resonant	Electrostatic	$k = 0$	$\mathrm{f}(\mathrm{t}) = -\mathrm{sgn}(\dot{\mathrm{z}}) \times \mathrm{F}$

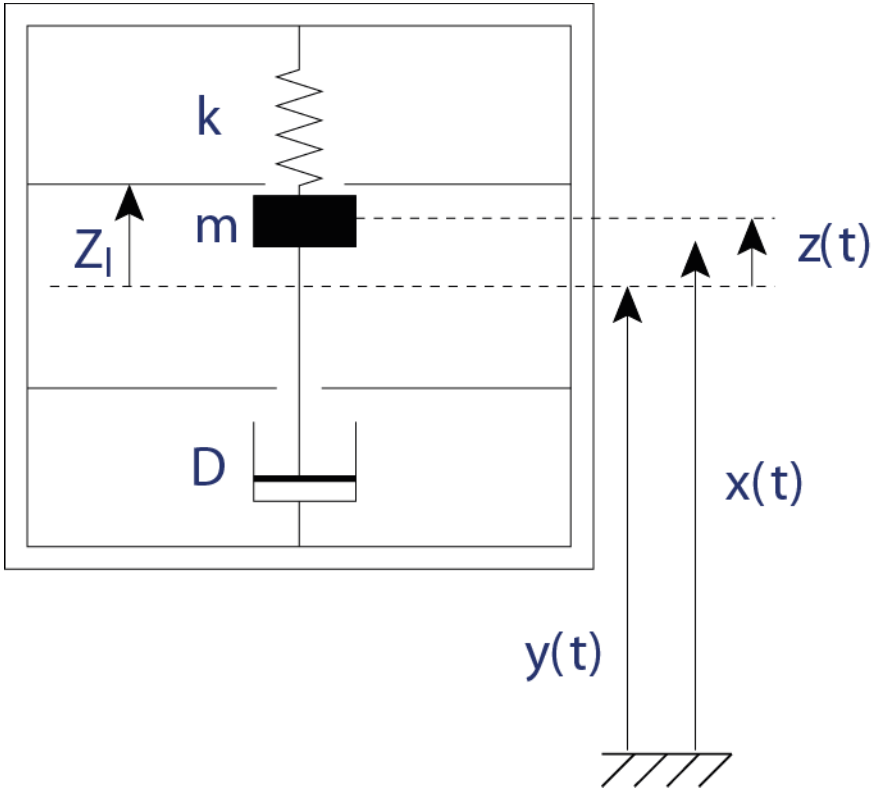
- Back of envelope calculation shows that the non-resonant velocity-damped generator is not practical on a small scale
- It would require more damping force than can be achieved with practical magnet/coil arrangements

Inertial Generator Architectures

- Three practical architectures
  - Velocity-Damped Resonant Generator (VDRG):
    Generator with a tuned mass-spring system and a linear damper
  - Coulomb-Damped Resonant Generator (CDRG):
    Generator with a tuned system and a non-linear damper
  - Coulomb-Force Parametric Generator (CFPG):
    System without a spring and with a non-linear damper

Which is the best? When? Let’s analyse them...

Velocity-Damped Resonant Generator



- Newton's 2*nd* Law:

$$m\ddot{z}(t) = -kz(t) - D\dot{z}(t) - m\ddot{y}(t)$$

- Transfer function:

$$\frac{Z(s)}{Y(s)} = \frac{-s^2}{s^2 + 2\zeta\omega_n s + \omega_n^2}$$

- Where:

$$\zeta = \frac{D}{2m\omega_n}, \omega_n = \sqrt{\frac{k}{m}}$$

Velocity-Damped Resonant Generator

- The frequency response:

$$\frac{Z_0}{Y_0} = \frac{\omega_c{}^2}{\sqrt{(1-\omega_c{}^2)^2 + (2\zeta\omega_c)^2}}$$

- Energy per cycle:

$$\mathrm{E} = 2\mathrm{D}\int_{\text{-}Z_0}^{Z_0} \dot{z}\,dz$$

- And thus:

$$\mathrm{P} = \frac{\zeta\omega_c{}^3 Y_0{}^2 \omega^3 m}{[1-\omega_c{}^2]^2 + [2\zeta\omega_c]^2}$$

VDRG – Maximising Power Density

- Find the optimal damping factor:

$$\frac{dP}{d\zeta} = 0$$

- This gives:

$$\zeta_{opt} = \frac{1}{2\omega_c}\sqrt{\omega_c^{\ 4} - 2\omega_c^{\ 2} + 1}$$

- But need to consider the constraints:
  - The limitation on Z_l
  - The maximum value of physical constants

We want to find the best value of ζ under all conditions

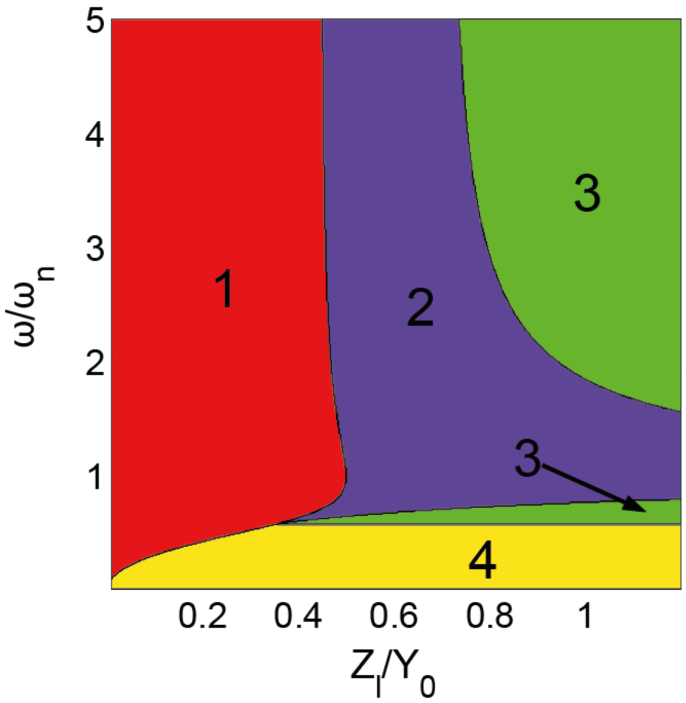
VDRG – Maximising Power Density

- The expression for maximum power density (under all conditions) can always be written as a function of:
  - The ratio of ω/ω_n
  - The ratio of Z_l/Y_0
- And can be normalised to:
  - The value of the proof mass
  - The cube of the input motion frequency
  - The square of the input motion amplitude

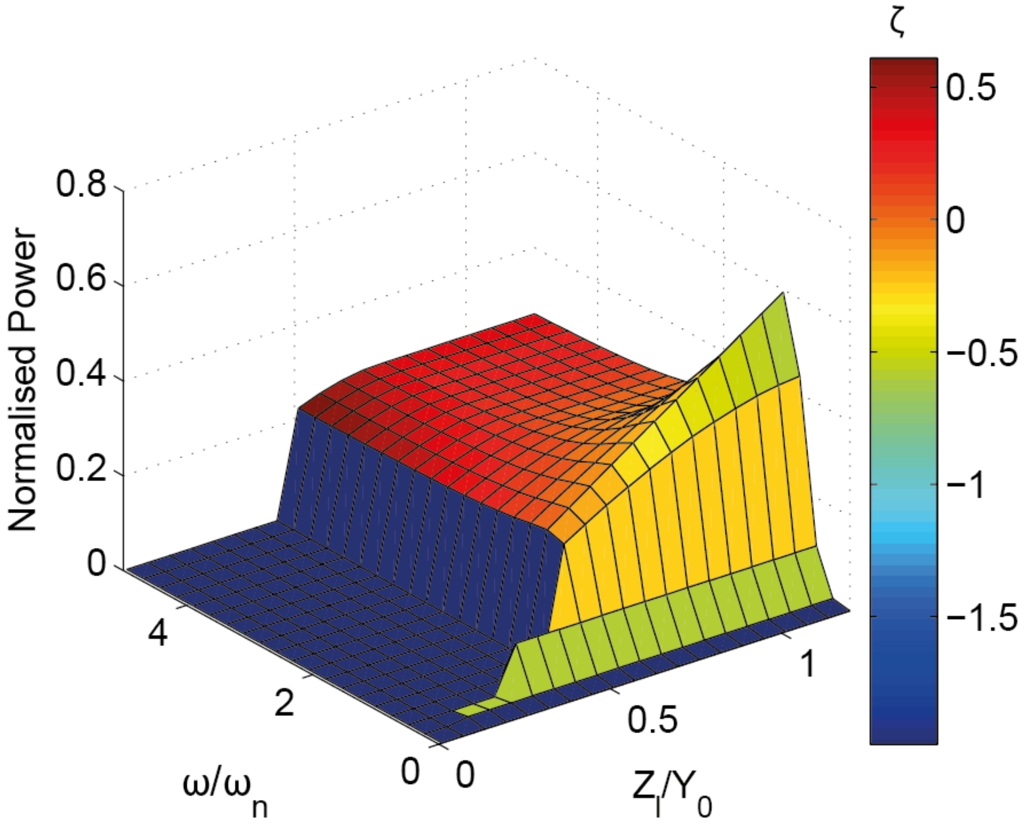
We can now plot an optimal performance surface...

VDRG Optimal Performance

m=0.5 g, B=1 T, N=10, R=1 Ω, ω=10 rads/s, A=1 cm^2



Operating chart

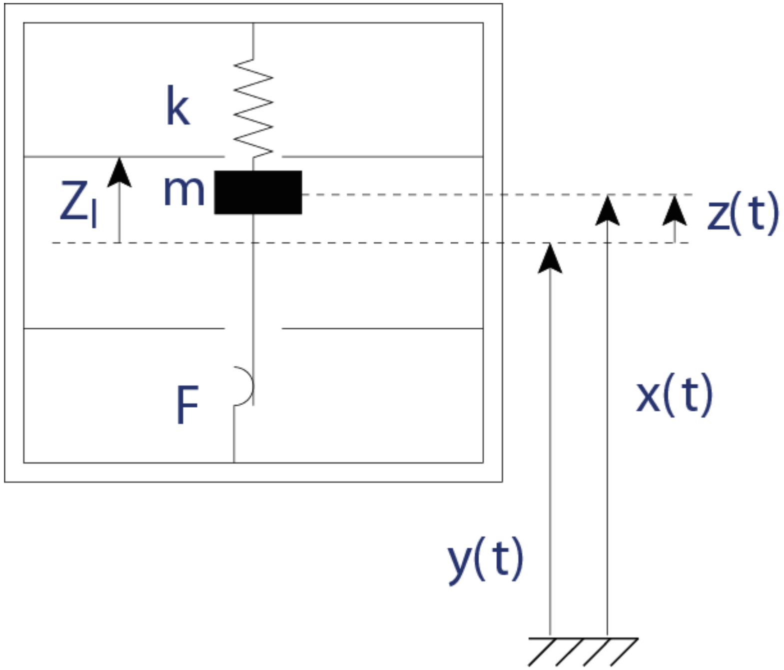


Maximum power

VDRG Operating Regions

- With reference to the operating chart on the previous page
  1. Device unable to operate, the required ζ to meet the displacement constraint being greater than the system can achieve.
  2. Power limited by Z_l - device operating at displacement limit
  3. Device operating optimally for the given value of ω_c.
  4. More power could be generated if the damping factor could be increased above the value of ζ_{max}.

Coulomb-Damped Resonant Generator



- Newton's 2*nd* Law:

$$m\ddot{z}(t) = -kz(t) - \mathrm{F}\times\mathrm{sgn}(\dot{z}(t)) - m\ddot{y}(t)$$

- Describing function:

$$\frac{Z_0}{Y_0} = \omega_c^{\,2}\left[\frac{1}{\left(1-\omega_c^{\,2}\right)^2} - \left(\frac{F}{mY_0\omega^2\omega_c}U\right)^2\right]^{\frac{1}{2}}$$

- Where:

$$U = \frac{\sin\left(\dfrac{\pi}{\omega_c}\right)}{\left[1+\cos\left(\dfrac{\pi}{\omega_c}\right)\right]}$$

Coulomb-Damped Resonant Generator

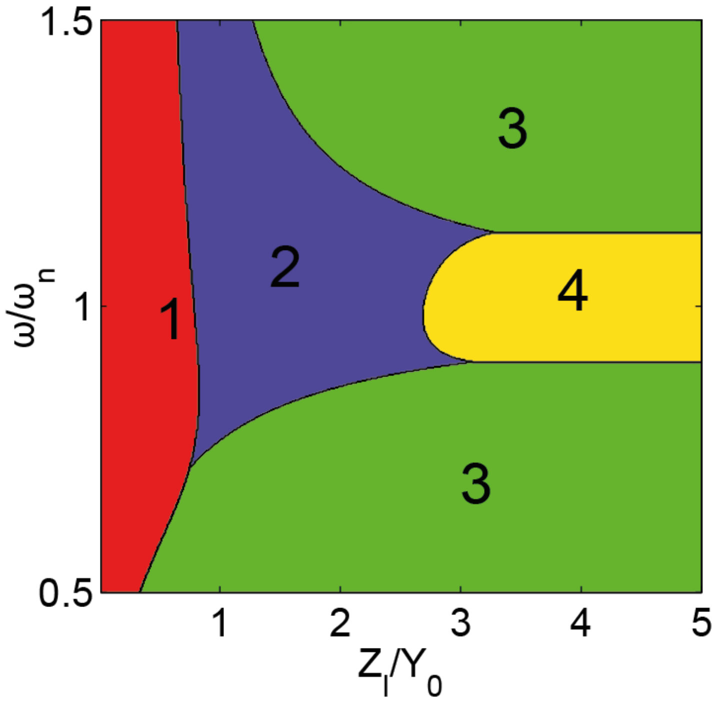
- The energy dissipated is given by the force-distance product, and thus the power is:

$$P = \frac{4Y_0 F\omega\omega_c^{\ 2}}{2\pi}\left[\frac{1}{\left(1-\omega_c^{\ 2}\right)^2} - \left(\frac{F}{mY_0\omega^2\omega_c}U\right)^2\right]^{\frac{1}{2}}$$

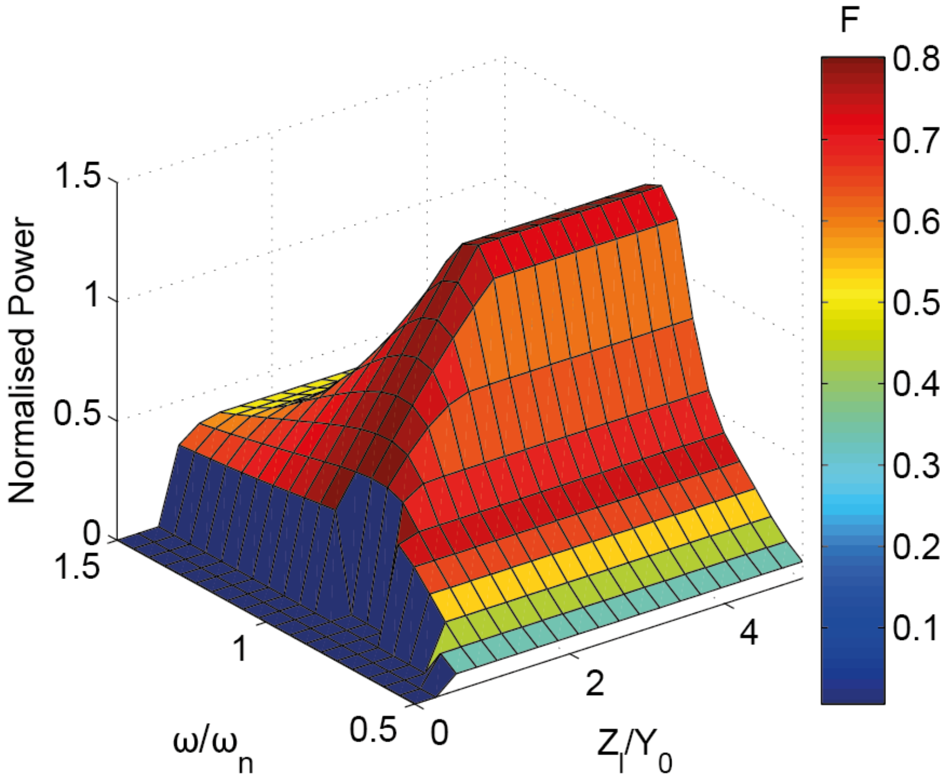
- We may now find the optimal damping force, and the operating regions as we did for the VDRG...

CDRG Optimal Performance

m=1 g, Y_0=1 mm, ω=20π, A=1 cm^2, V_{max}=450 V



Operating chart

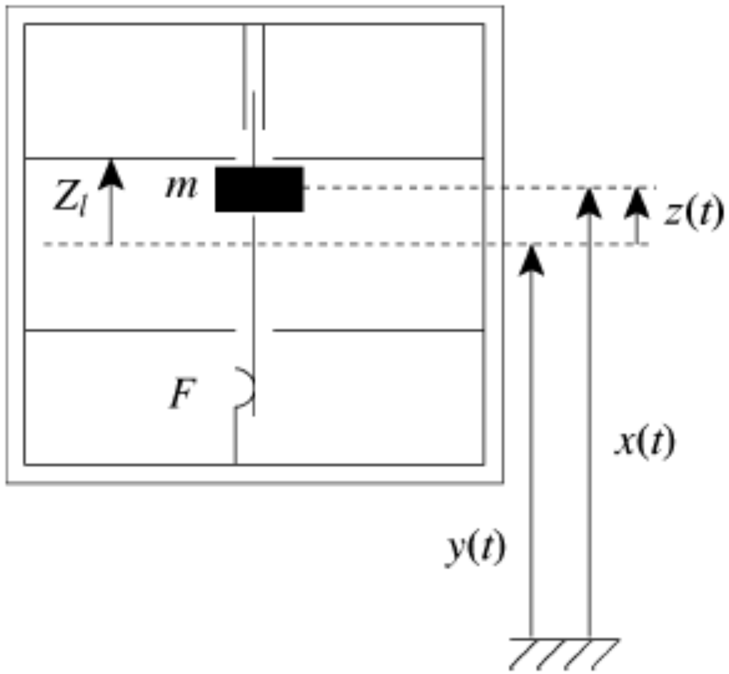


Maximum power

CDRG Operating Regions

- With reference to the operating chart on the previous page
  1. Device can't operate without stops in motion (non-linear damper can cause stop-start motion)
  2. Power limited by Z_l - device operating at displacement limit
  3. Device operating optimally for the value of ω/ω_n
  4. Device operation limited by maximum voltage

Coulomb-Force Parametric Generator



- Maximum inertial force on mass:

$$mY_0\omega^2$$

- Thus energy per stroke is the force distance product:

$$E = \beta m Y_0 \omega^2 Z_0$$

- β is the break-away factor and is less than 1 (in order for the mass to move some distance the force must be a fraction of the maximum inertial force)

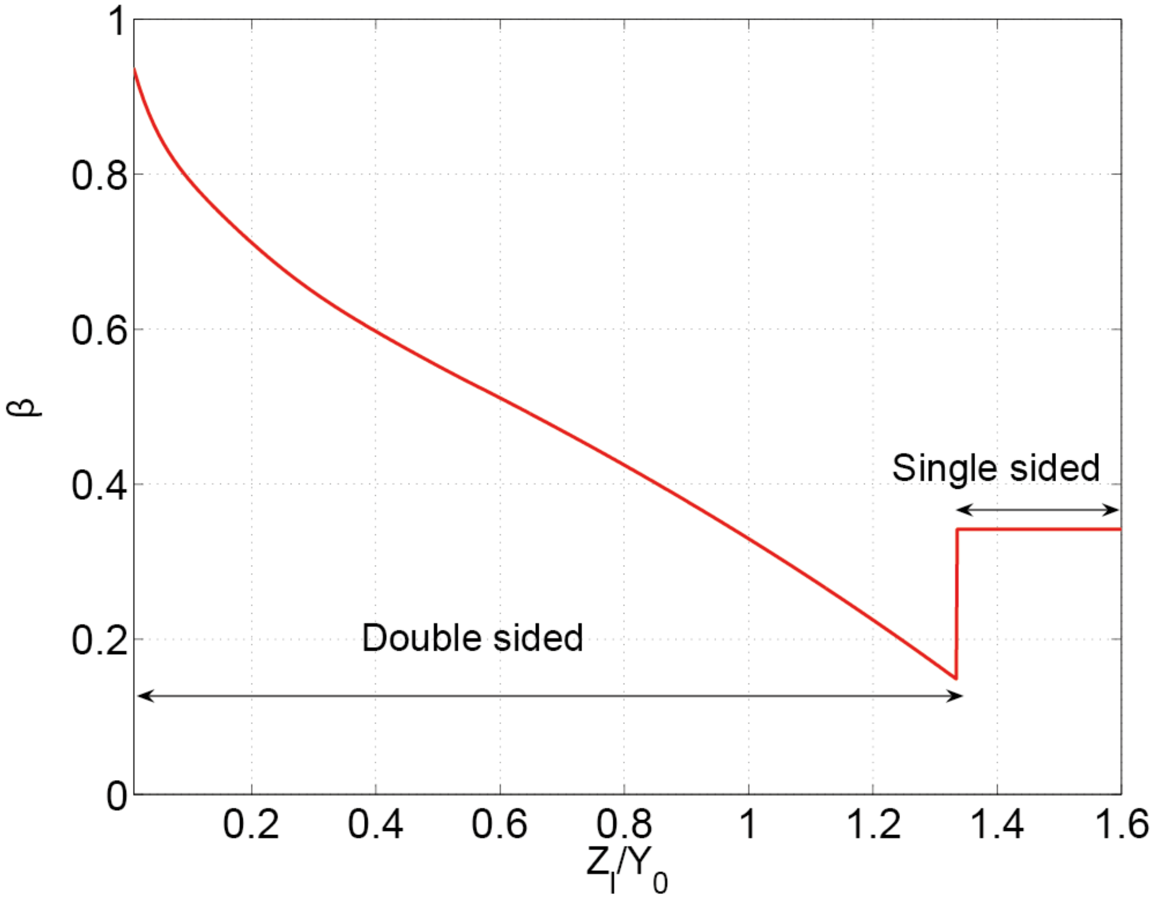
Coulomb-Force Parametric Generator

- Thus, the power is given by:

$$P = 2\beta\left(\frac{Z_0}{Y_0}\right)\frac{Y_0^{\ 2}\omega^3 m}{\pi}$$

  - There is an optimal β
  - Must maximise βZ_0 product
  - Maximum value of Z_0 is Z_l
  - Can't solve for β_{opt} analytically...

Coulomb-Force Parametric Generator

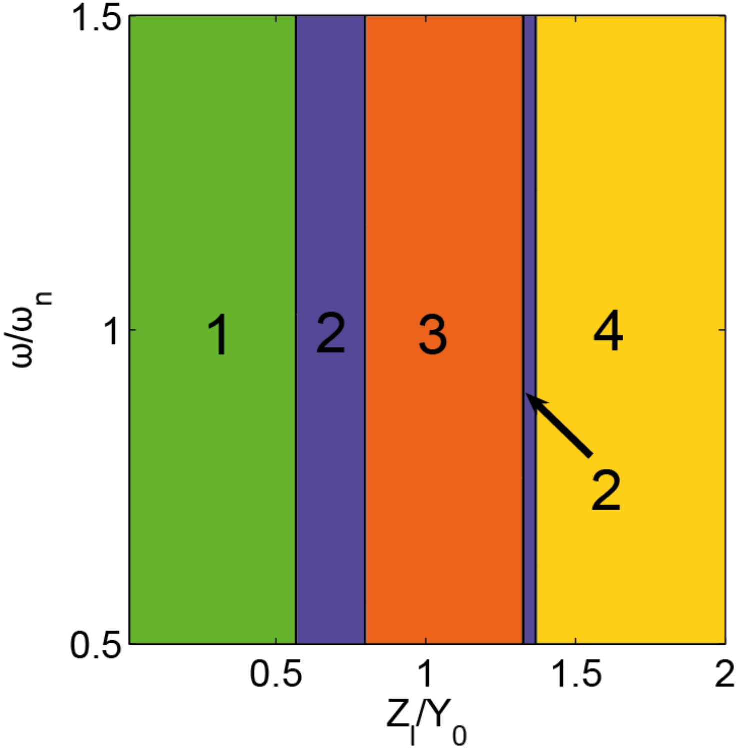


- β_{opt} calculated numerically from simulation
- Polynomial fitted to the results (shown)
- Change from double to single sided operation

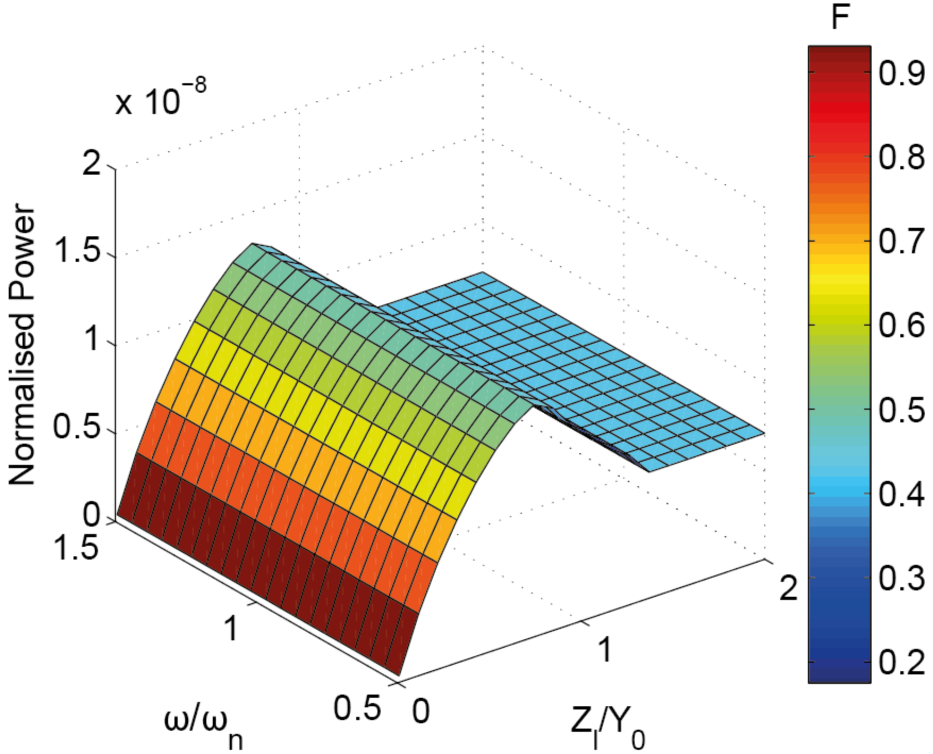
- Now we know *β* we can plot the optimal performance...

CFPG Optimal Performance

m=1 g, Y_0=0,5 mm, ω=2π, A=1 cm^2, V_{max}=110 V



Operating chart



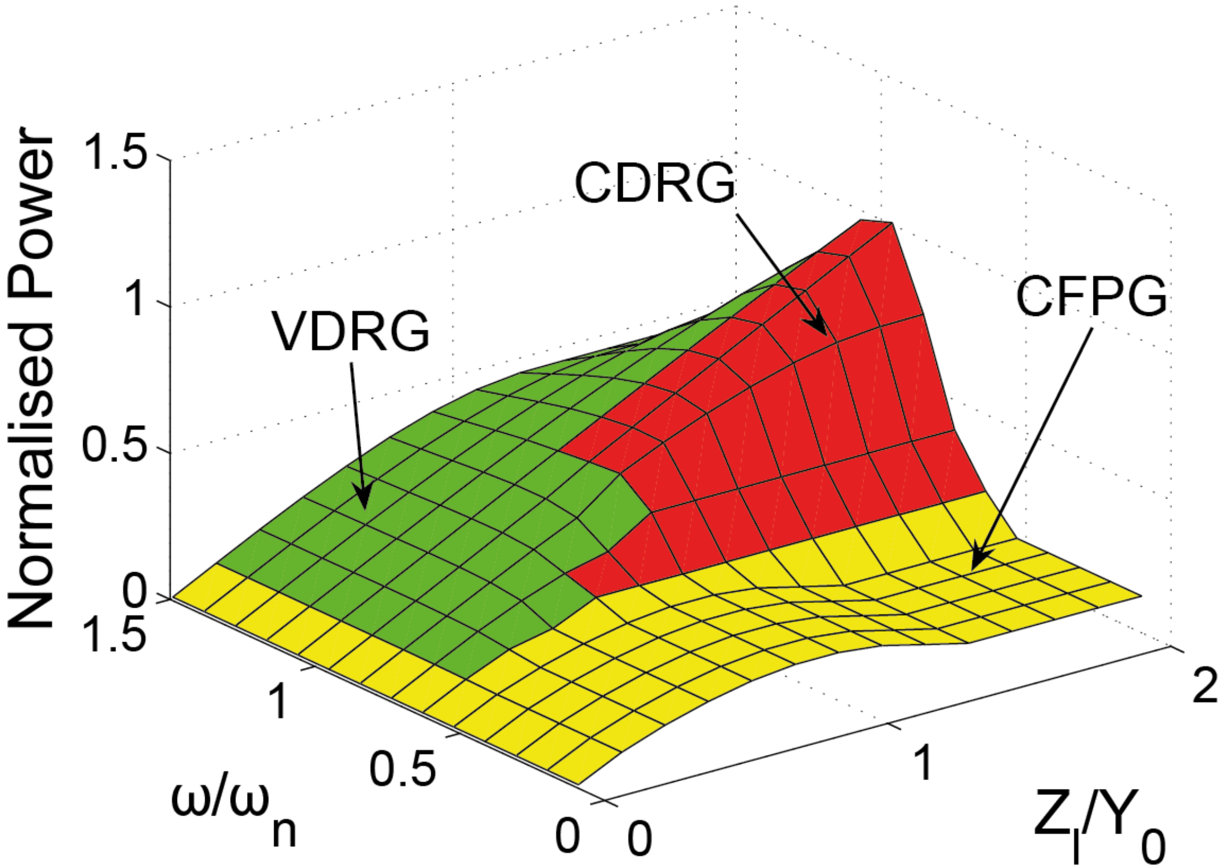
Maximum power

CFPG Operating Regions

- With reference to the operating chart on the previous page
  1. Optimal double-sided operation
  2. β reduced to allow double sided operation
  3. Device in voltage limit – more power could be generated if the device was allowed to operate at over 110 V
  4. Single sided mode and device still in voltage limit

We can now compare the three architectures...

Architecture Comparison



Maximum performance under varying operating conditions

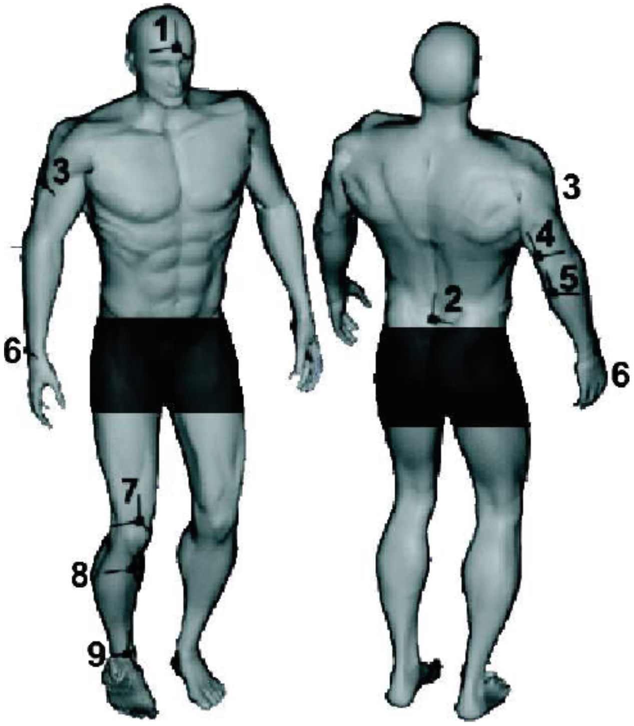
Architecture Comparison

- Resonance only useful when Z_l/Y_0 is large
- Very little difference between the VDRG and CDRG – choice mainly down to implementation and scaling
- CFPG better when Z_l/Y_0 small – implanted devices powered from human body motion
- The CFPG doesn't have a resonant system to be tuned

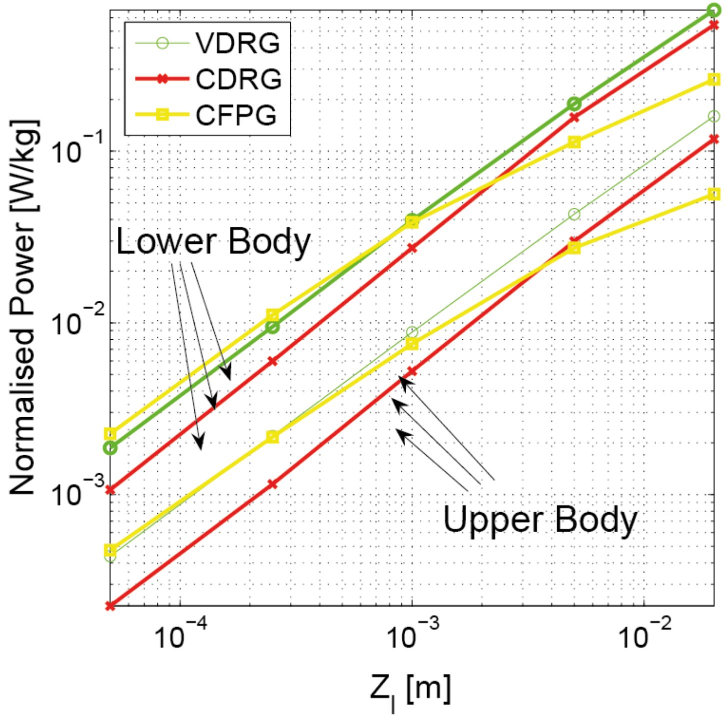
But how do the generators perform on signals more complex than single sinusoids?

Human Powered Generators

Power from non-sinusoidal motion [8]



Sensor positions



Performance comparison

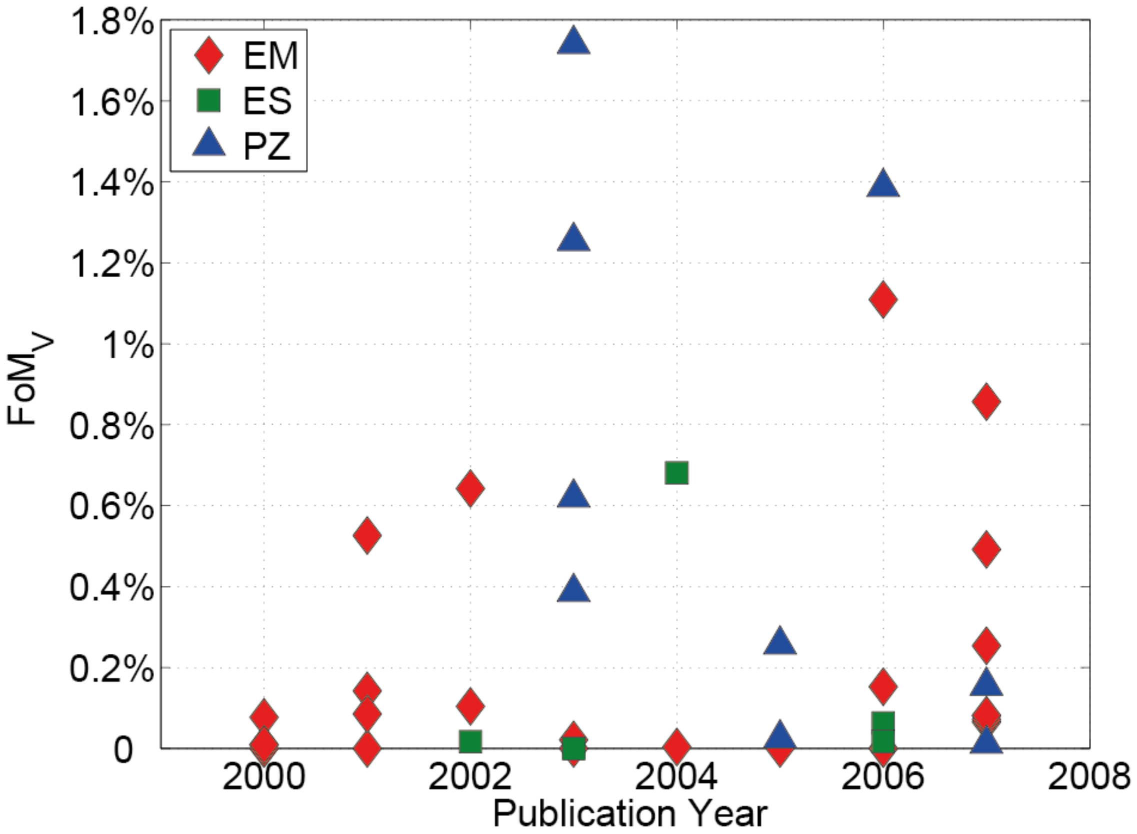
This work was in collaboration with T. von Büren at ETH Zurich

Effectiveness of Microgenerators

- The efficiency is actually an effectiveness
- Many people have suggested different formulae
- Fights can break out whilst discussing this!
- I would argue there is only sensible metric...
- A figure of 100% on this scale is the absolute best you can do
- We call this metric Volume Figure of Merit

Effectiveness of Inertial Microgenerators

$$FoM_V = \frac{\text{Useful Power Output}}{\frac{1}{16} Y_0 \rho_{\mathrm{Au}} \mathrm{Vol}^{\frac{4}{3}} \omega^3}$$



- Volume Figure of Merit
- Lots of room to improve!
- Not enough data yet on rotational case

Summary of Harvester Fundamental Analysis

- We analysed the limits of power conversion using an inertial generator mass in a box model
- Power is maximised at resonance
- Power is proportional to the proof mass
- Power is proportional to the internal displacement
- Different damper types perform slightly differently but when optimised the limits are the same
- Resonance is useful when the device is larger than around 10 times the driving displacement amplitude
- For these systems power can always be normalised to $Y_0^2 \omega^3 m$

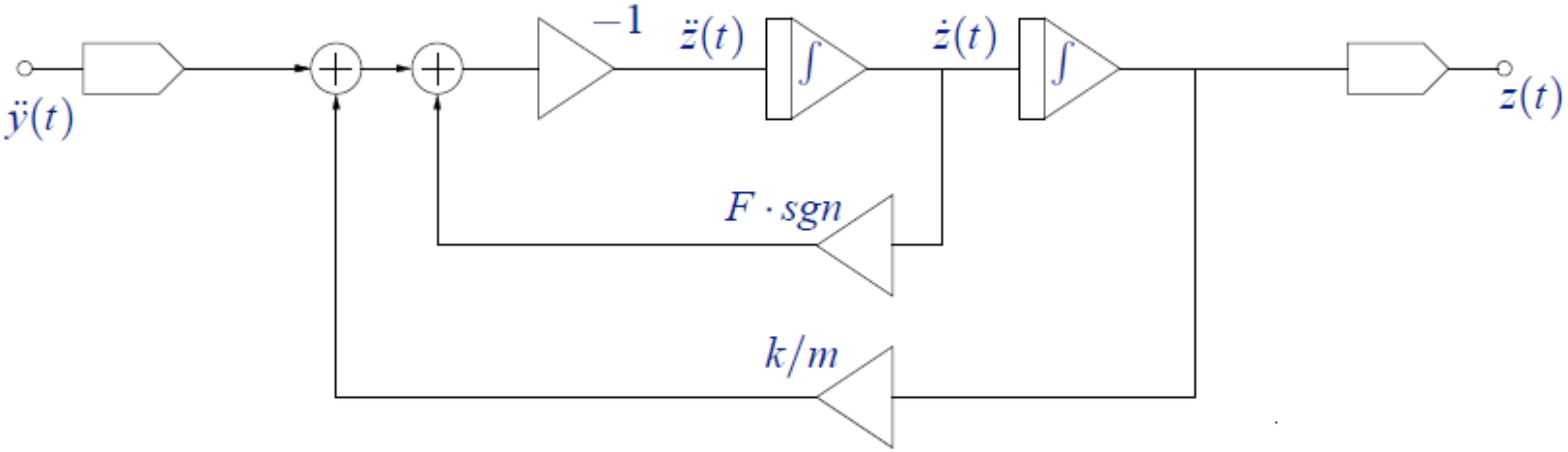
System Modelling and Simulation Approaches

Modelling Overview

- All our analysis so far has involved closed form algebra
- The damper characteristic is critical to the analysis
- Takes into account the coupling between mechanical and electrical
- “Simple” to analyse when the load is linear or switched on an electrostatic (because the damping characteristic is known)
- What type of model could we use for a complete electromechanical system analysis and simulation?
- The right model can give very good insights…

One Potential Modelling Strategy…

- Normal type of simulation diagram used in Simulink

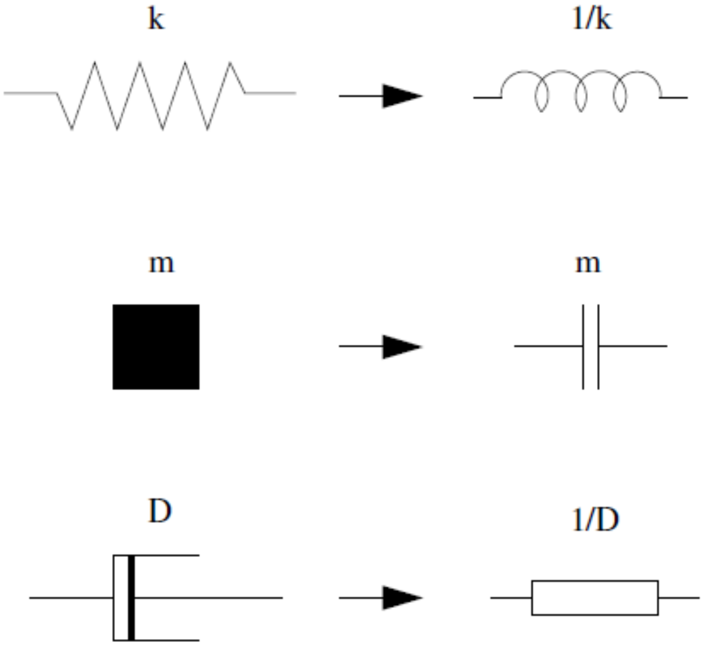


- This is a mixed electromechanical system model of a CDRG
- Probably also should include fluids effects, careful fields analysis too
- Allows time domain simulation… but does it give any real insight?

Electrical/Mechanical Analogy

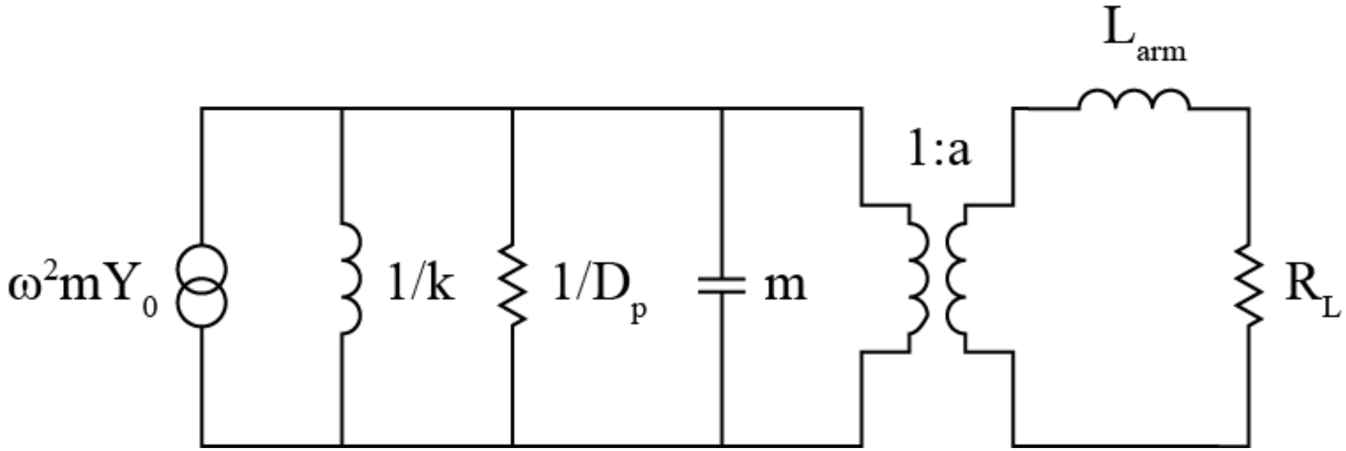
- Rather useful is the analogy between Newtons's second law and Kirchoff's voltage law.
- The equations which describe a mass-spring-damper system are identical in form to those describing an RLC oscillator
- The mapping can be done using one of two conventions,
  - f->V, (flow, or velocity, corresponds to voltage
  - e->V (effort, or force, corresponds to voltage)

f->V mappings



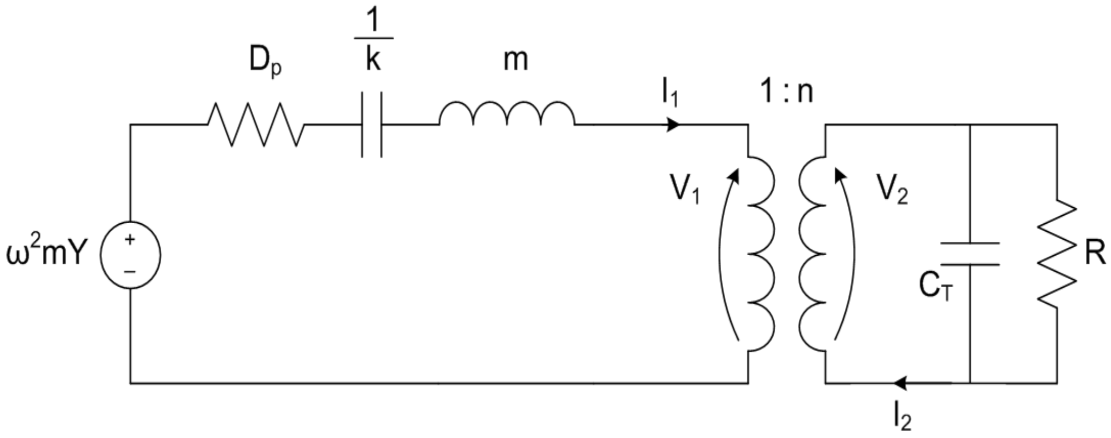
Electromagnetic Harvester Model (f->V)

- Immediately you can see what happens when you operate at, or away, from resonance.
- You can also see what you need to do to maximise power with parasitic damping present



Piezoelectric Harvester Model (e->V)

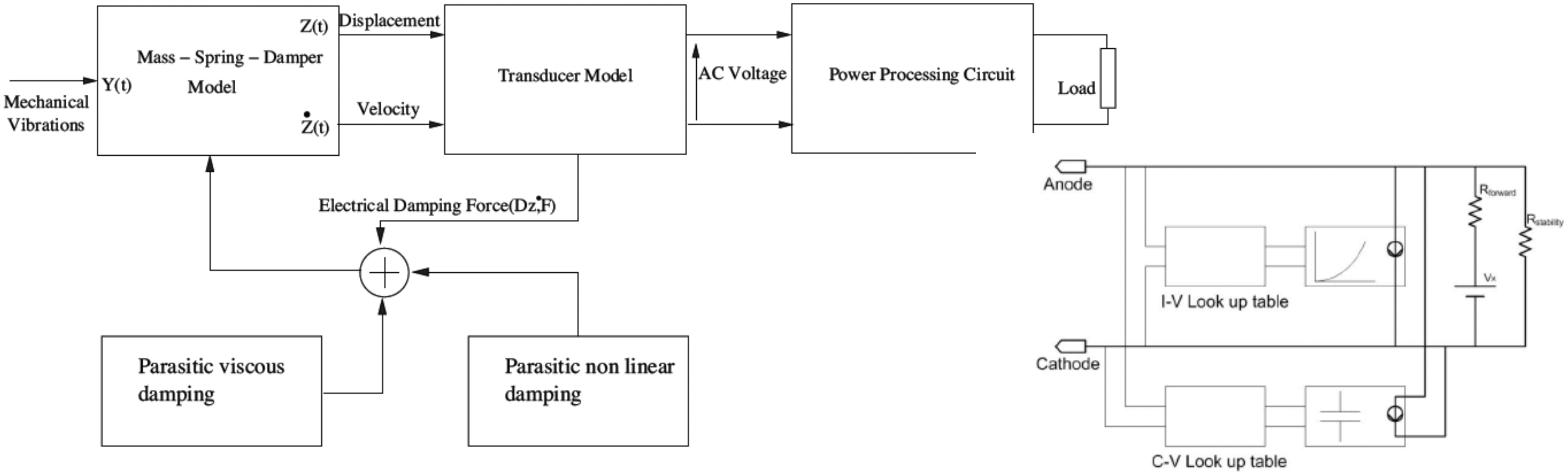
- More sophisticated to model the interaction between the load and the generator



- This can be modelled in SPICE and can allow the load circuit to be modelled with good device models

More Sophisticated Models

- Include the non-linear mechanical components (mass limited travel, spring hardening)
- Include custom semiconductor device models
- All done in SPICE – Imperial College Energy Harvesting Toolkit (ICES)

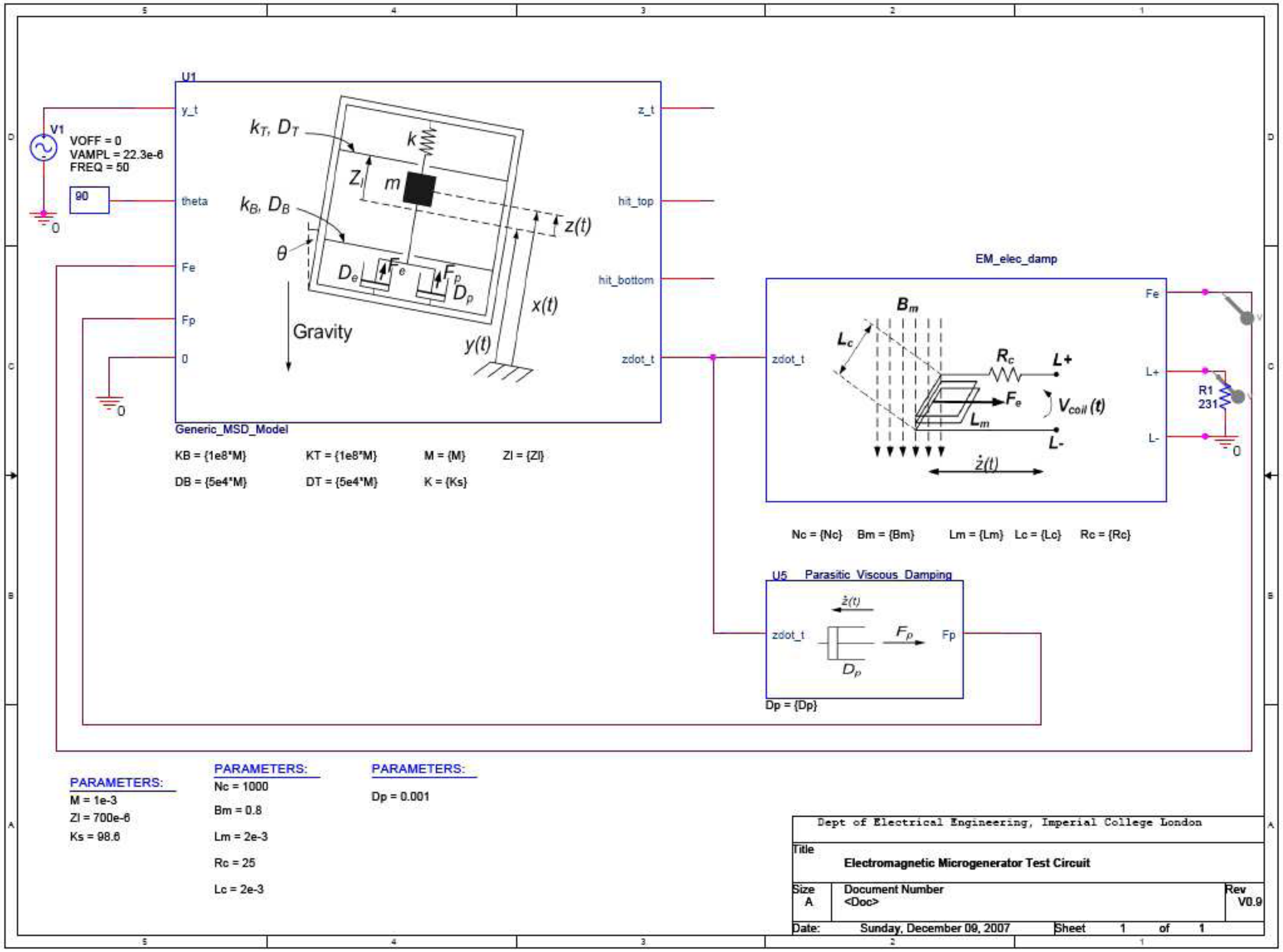


Kondala Rao G, Mitcheson PD, Green TC, Mixed Electromechanical Simulation of Electrostatic Microgenerator Using Custom-Semiconductor Device Models, PowerMEMS 2009, Pages:356-359

Detailed Mechanics

Custom device model

ICES Toolkit



http://www3.imperial.ac.uk/controlandpower/research/portfoliopartnership/projects/powermems/simulationtoolkit/

Transducers and Power interface Requirements

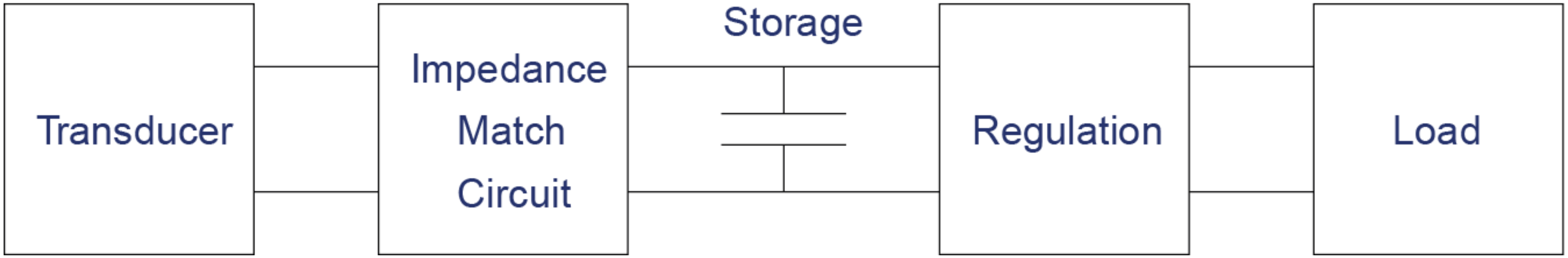
Transducer Considerations

- With the right electronics, any type of transducer can give any force characteristic
- Easier to make linear damper with electromagnetic and piezoelectric
- Easier to make Coulomb damper with electrostatics
- Scaling laws are important:
  - electrostatic forces dominate at small size
  - electromagnetic are better at larger sizes

Choice of transducer depends on scale and difficulty of implementation

Transducer/System Electronics

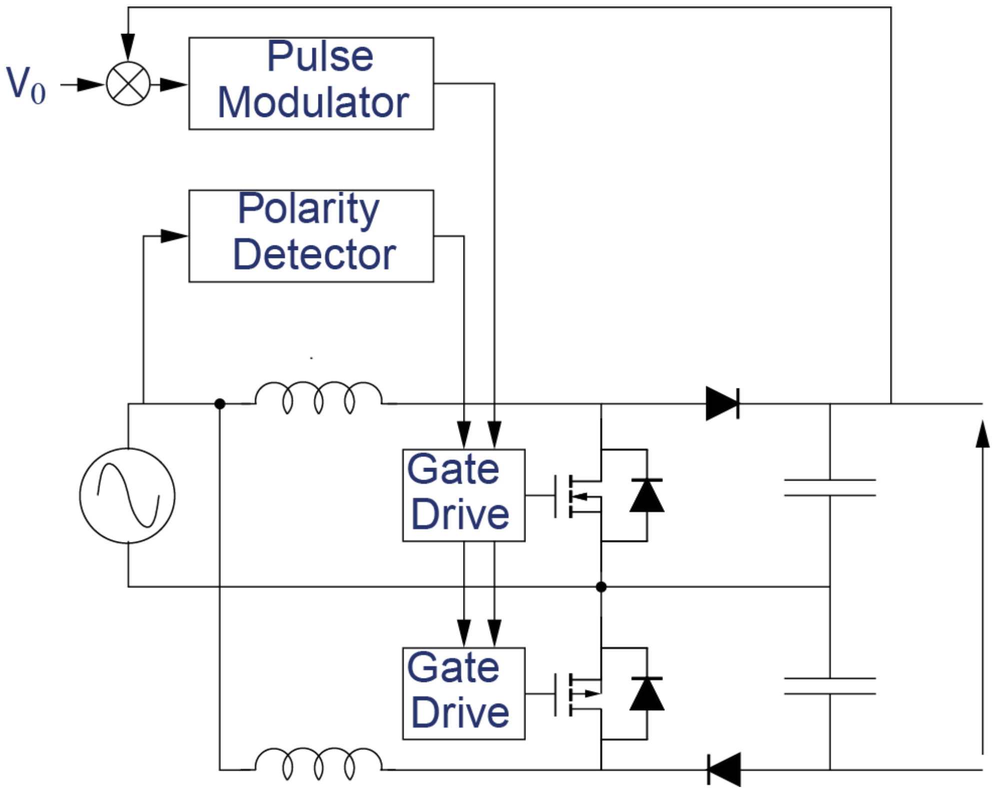
- Need electronics to present optimal load to transducer - impedance match
- This ensures maximum power generation
- Actual load electronics probably not optimal
- Transducer voltage is AC - load wants regulated DC
- Energy storage needed as harvester is intermittent



Electromagnetic Transducer - requirements

- Voltage from generator is typically small - must be stepped up
- Must draw a specific peak current from generator to keep the optimal damping force
- Resistive is more optimal than an imaginary or non-linear load
- Need power converter with controlled resistive input impedance
- This will create a linear damping

Proposed El.-mag. Circuit



- Boost topology for step-up
- Draws an in-phase sinusoidal current from a sinusoidal voltage source
- Two converters eliminate need for diode rectifier
- Alter damping by altering duty cycle

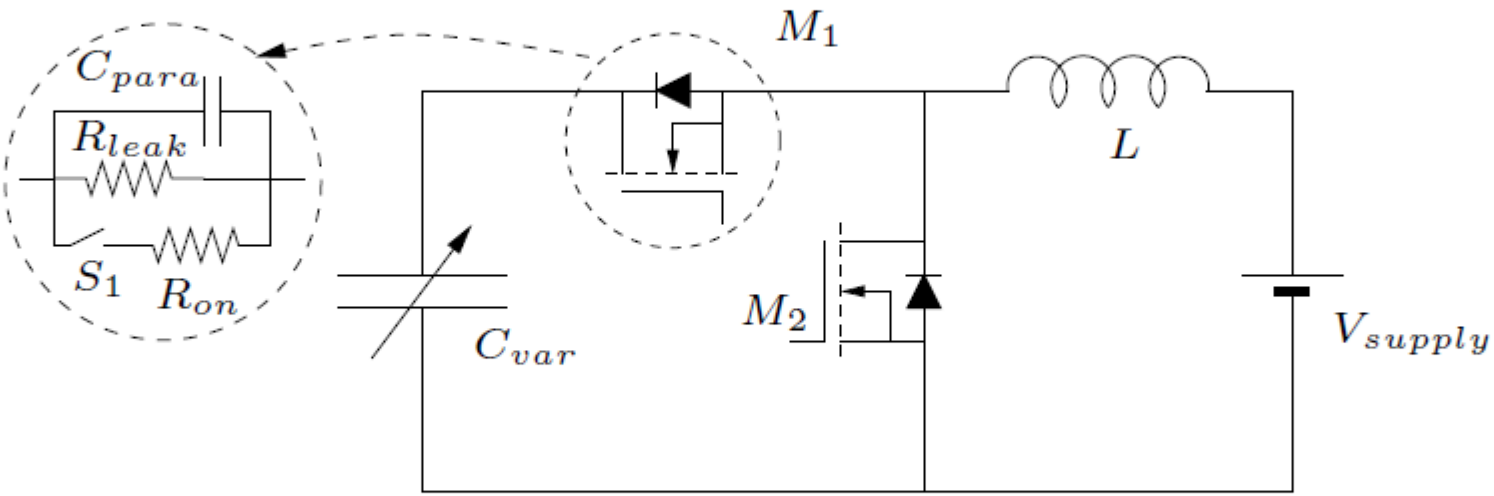
Summary of Electromagnetic Transducer

- Transducer produces low voltage
- Difficult to rectify with diodes
- Control coil current to control damping force
- Makes a linear transducer (assuming coil inductance ignored)
- Scaling laws suggest it's ok for macro-scale, but not micro-scale

Electrostatic Transducers - requirements

- Capacitor must be precharged to correct voltage
- Voltages from generator tend to be very high. Step down circuitry required.
- The capacitor must be electrically isolated for const Q part of the cycle - $10^{12}\Omega$ blocking impedances required.
- Trade-off: Large area semiconductors keep conduction loss low but have high parasitic capacitance and leakage.

Electrostatic Transducers – proposed circuit



- Buck topology
- Allows controlled charge and discharge of variable C

Summary of Electrostatic Transducer

- Transducer produces very high voltage
- Difficult to block with integrated pn junctions
- Control capacitor priming voltage to control damping force
- Makes a non-linear transducer (Coulomb-force)
- Scaling laws suggest it’s ok for micro-scale, but not macro-scale

Piezoelectric Transducer

- Typically cantilever structures to give mechanical gain
- Makes it easier to get a large strain on the piezo
- Using a resistive load (resistive input converter) often cannot achieve enough damping
- Especially at high frequency due to shunt C_0
- Voltages and currents are reasonable

Let's look at a specific example to tie all we have done together

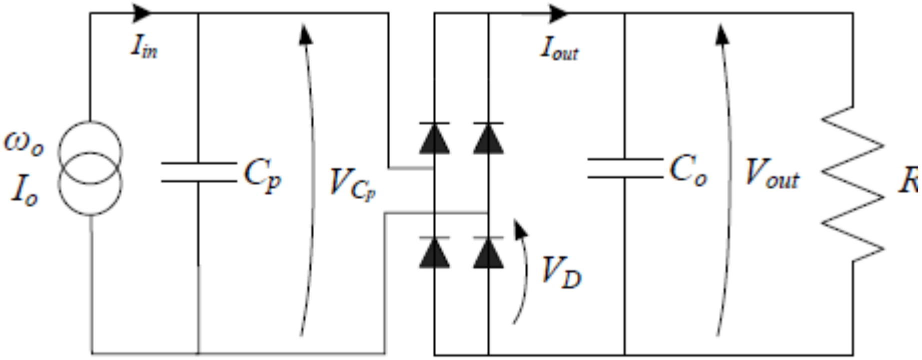
Piezoelectric Harvester System Example

Power-extraction circuits for piezoelectric energy harvesters in miniature and low-power applications
J Dicken, PD Mitcheson, I Stoianov, EM Yeatman
Power Electronics, IEEE Transactions on 27 (11), 4514-4529

Piezoelectric Harvesters

Piezoelectric harvesters produce AC outputs

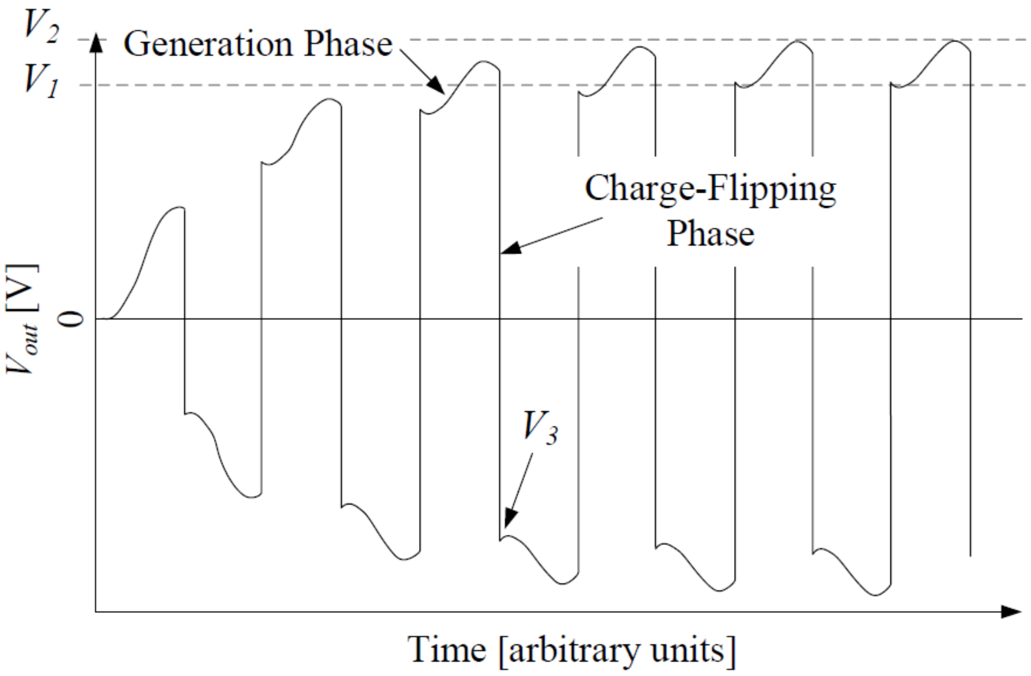
- Must have rectification
- May require step up or down depending on open circuit voltage of piezo

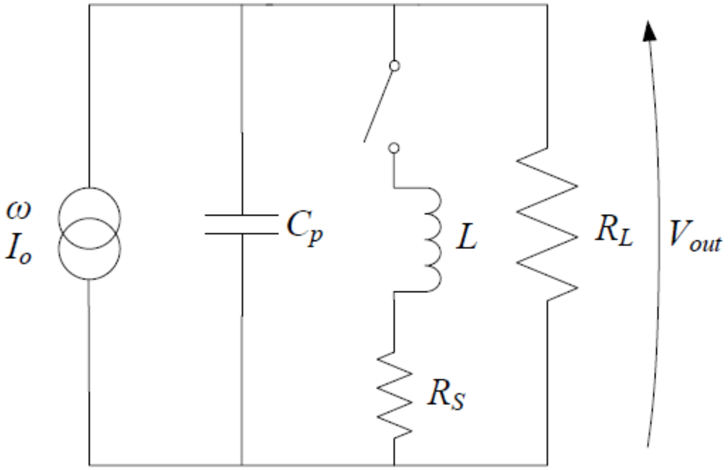


- But can we extract maximum power?

- As we know, piezo material coupling can be low. This means it is often hard to achieve the optimal electrical damping

Modify the voltage waveforms on the piezo





Often referred to as SSHI

- Charge on capacitor is resonantly flipped at voltage peaks
- Even in open circuit, a finite maximum amplitude is reached due to finite circuit Q-factor

It's a Coulomb Damper now!

Remember the force on the piezoelectric material is:

$$F(t) = K_{PE} z(t) + \alpha V(t)$$

Where K_{PE} is the beam short circuit stiffness.

This can be written as:

$$F(t) = K_{OC} z(t) + \alpha Q(t) / Cp$$

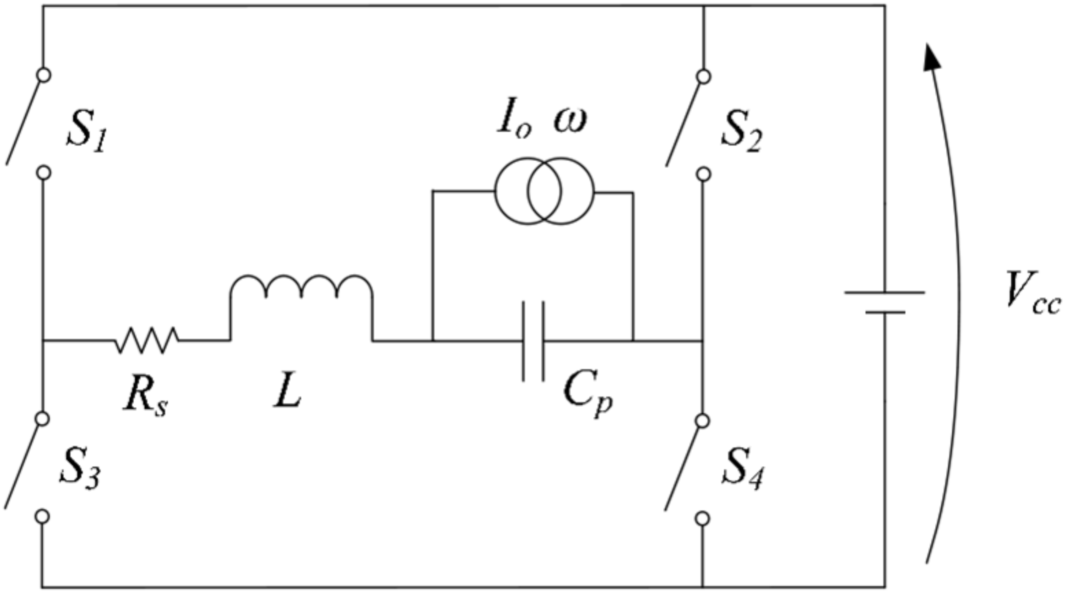
Where K_{OC} is the open circuit stiffness and Q(t) is the external charge places on the piezoelectric material

- Hence, pushing a fixed Q onto the capacitance at the star and end of the cycle can create a Coulomb damper whose value we can control!

Single Supply Pre-biasing Circuit Overview

Simplified and improved circuit to achieve the waveform modification

- Single source pre-bias circuit
- Source supplies pre-charge
- Generated energy returned to same source
- Can be made diode-less (with no free wheeling currents) if V_{CC} is optimally set



Let's see how it works…

Power Output Formula

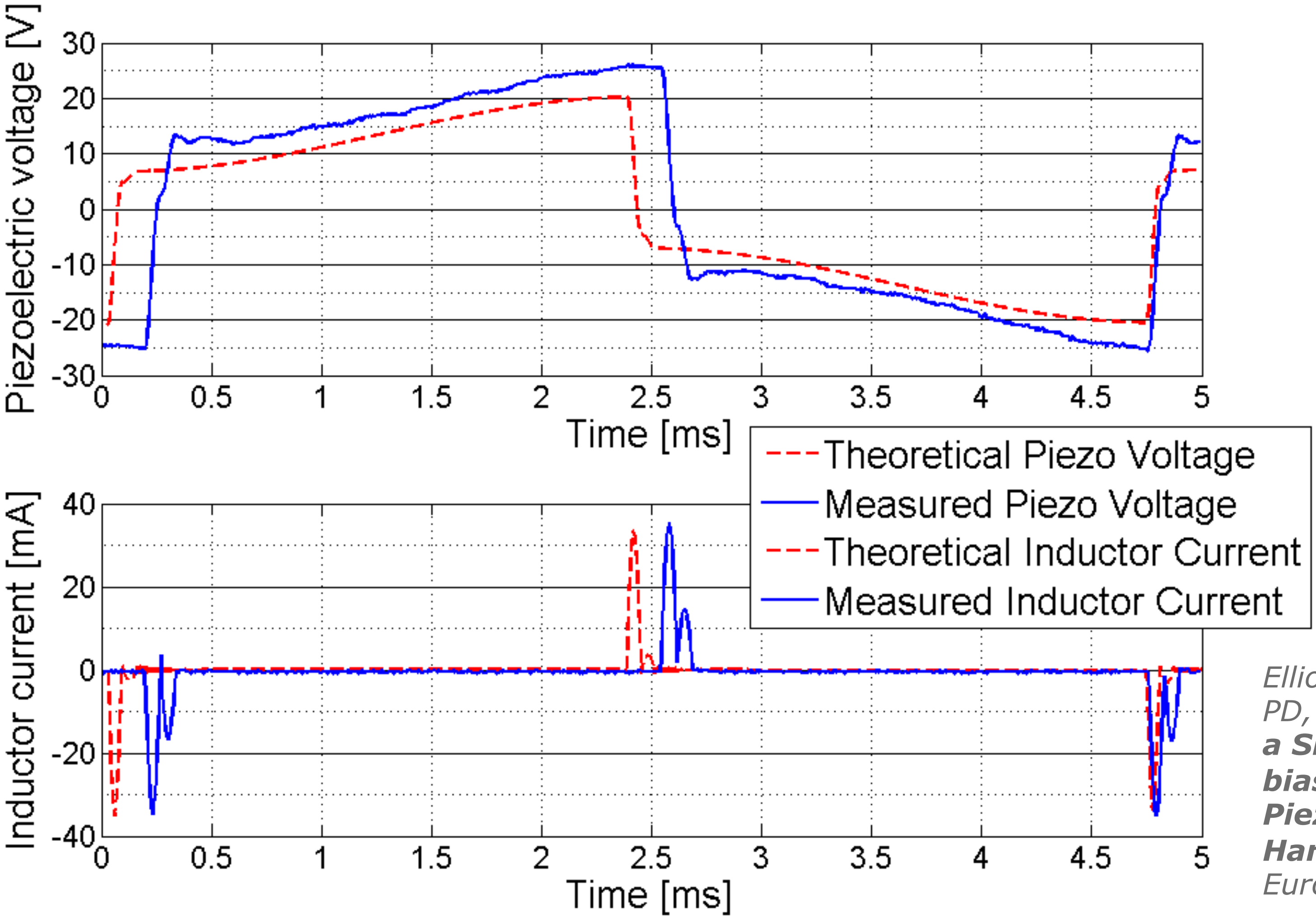
$$P_{\max} = V_{po}{}^{2} f_o C_p \left(\frac{8Q}{\pi} \right)$$

- V_{po} is the open circuit voltage of the piezo
- f_o is the mechanical excitation frequency
- Q is the quality factor of the resonant charging path
- C_p is the capacitance of the piezo

Dicken J, Mitcheson PD, Stoianov I, et al, ***Power-Extraction Circuits for Piezoelectric Energy Harvesters in Miniature and Low-Power Applications****, IEEE Transactions on Power Electronics, 2012, Vol:27, Pages: 4514-4529, ISSN:0885-8993*

Imperial College London

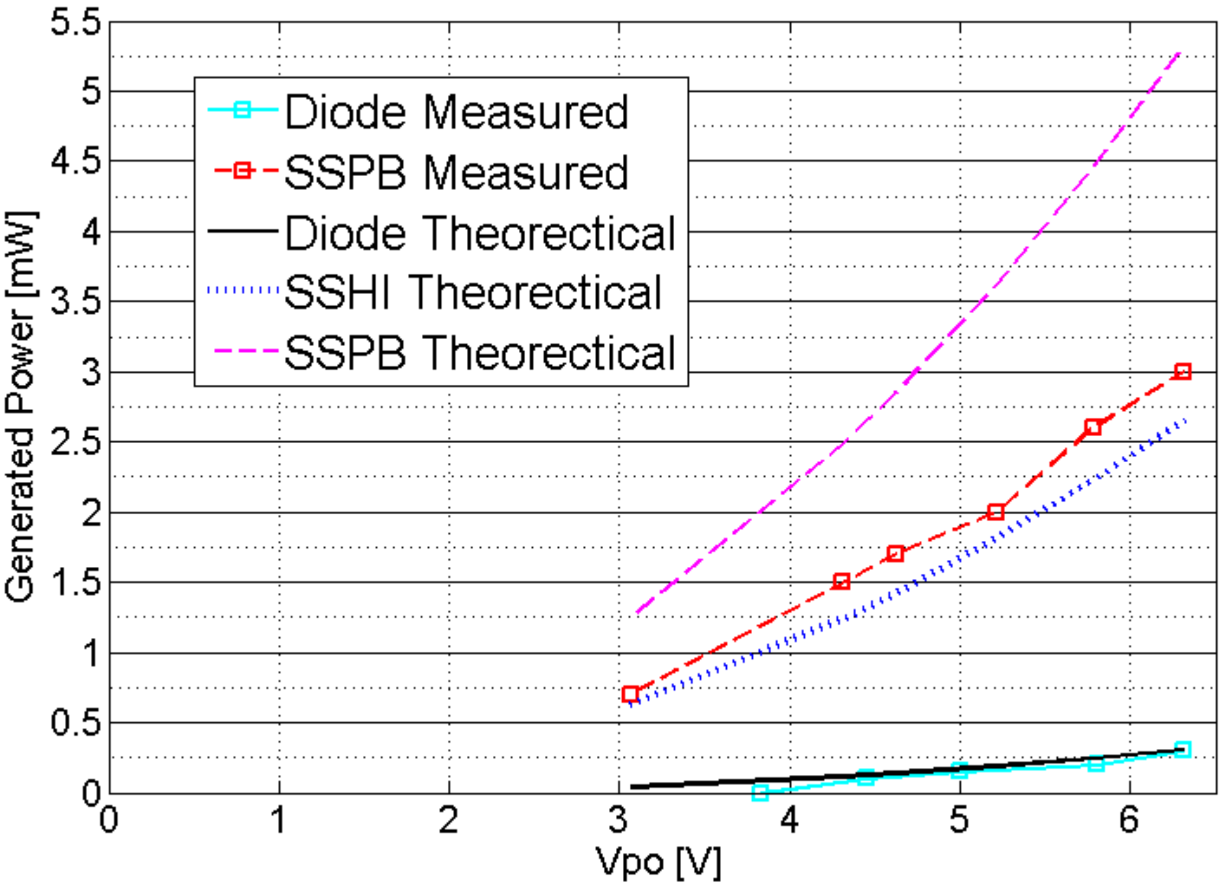
Results - Waveform



*Elliott ADT, Mitcheson PD, **Implementation of a Single Supply Pre-biasing Circuit for Piezoelectric Energy Harvesters**, Eurosensors 2012, 2012*

Results – Technique Comparison

- 400 µW control power consumption
- 2.6 mW useful power generated
- 6 times more power extracted than diode rectifier
- Theoretically twice as much power as SSHI



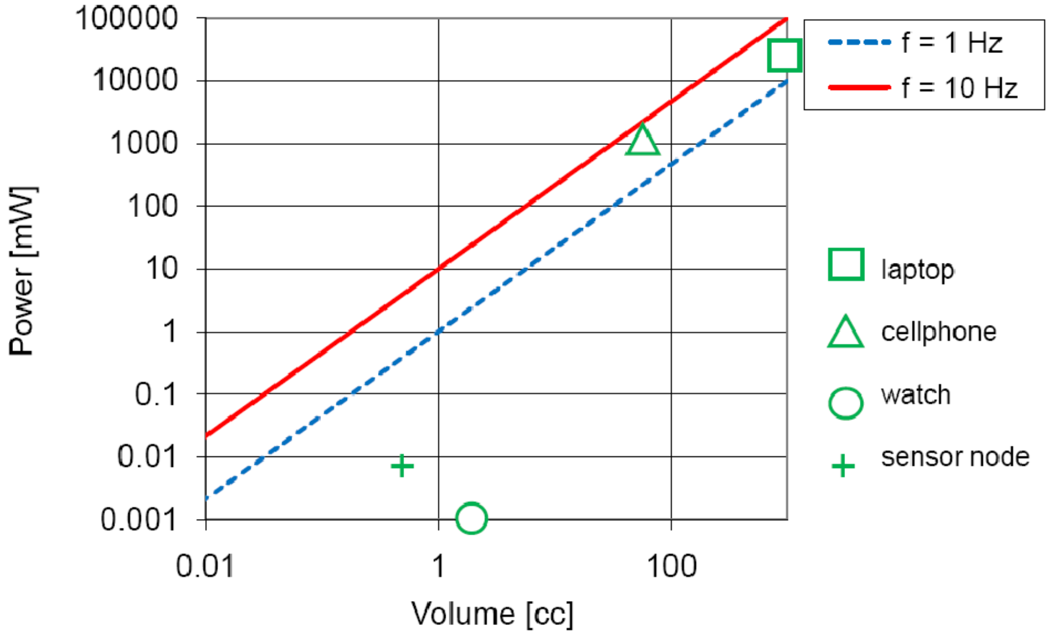
Measured SSPB = 1.13 x SSHI(theoretical)

Conclusions

- Motion-driven energy harvesters are still performing at a level far below what is theoretically achievable
- Current performance is adequate for some applications such as machine monitoring, and commercial solutions are emerging here
- Significant improvements in performance will be required before harvesting power from human body motion can become viable
- Power conditioning is very important in making a working energy harvester – and a real challenge
- The **system** is important – and being able to analyse the system including the strong link between electric circuit and mechanical systems is important

Why is it difficult to realise a self powered WSN?

What can we power from low frequency vibrations?



- *1g acceleration*
- *Watch relatively easy to power*
- *Sensor node is around 2 orders of magnitude harder*
- *Forget the laptop and cell phone for several years…*

We have to optimise the system globally to have a chance of making it functional

Acknowledgements

Eric Yeatman, Andrew Holmes, Tim Green, Tzern Toh, Kondala Rao, Lauriane Thorner, James Dicken, Peng Miao, Bernard Stark, Anisha Mukherjee, Alwyn Elliott

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