Vibration Energy Harvesting for Civil Infrastructure Monitoring

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Centre for Smart Infrastructure and Construction

- Much of our critical built infrastructure is ageing and not adequately monitored.
- There is a poor understanding of the performance of infrastructure during construction and use.
- The CSIC aims to develop a range of new underpinning technologies to address the monitoring and management of large-scale built infrastructure.
  - Wireless Sensor Networks.
  - Fibre optic sensors.
  - Computer Vision.
  - Data Analysis and Modelling.

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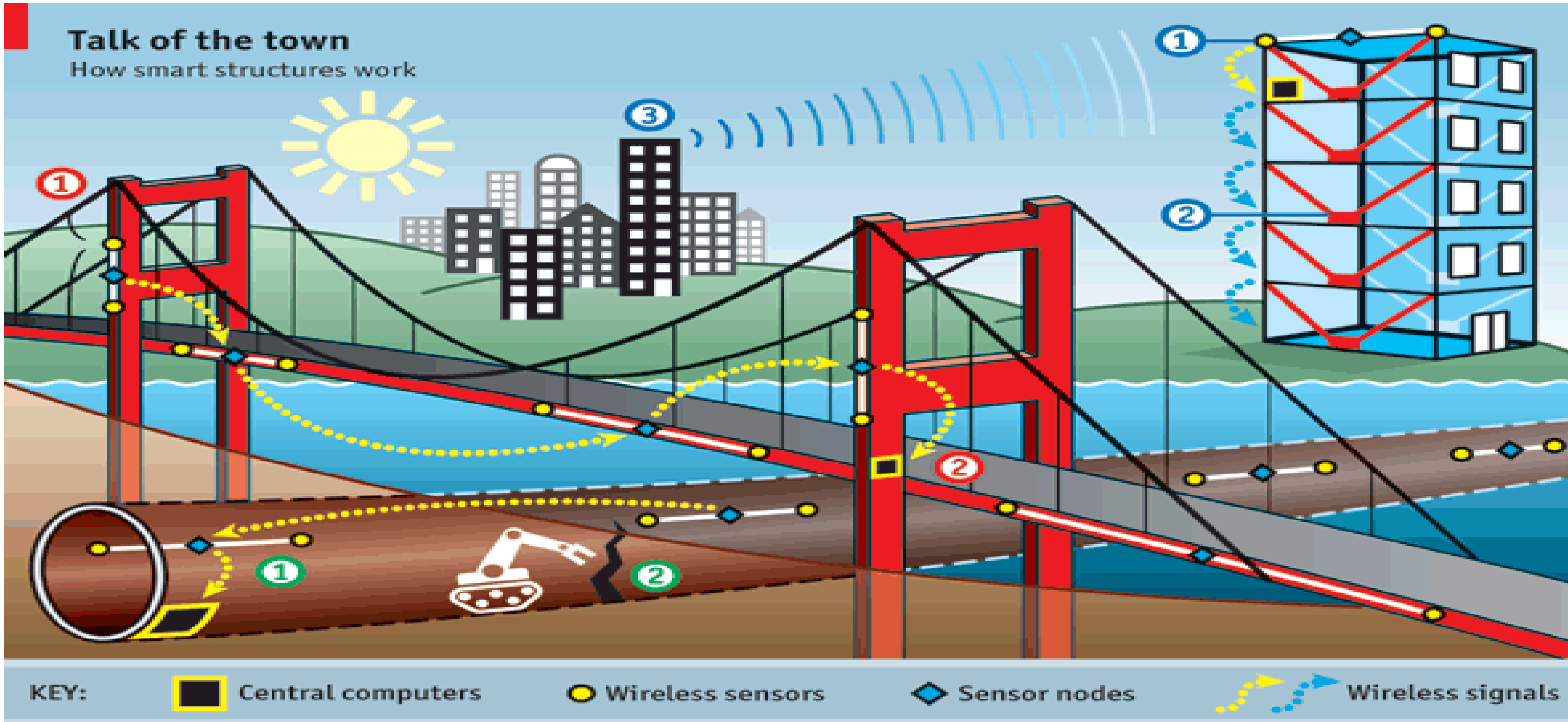
Smart Structures



SMART BUILDING

1. Sensors in a building monitor the building's movement in response to strong winds or earthquake tremors.
2. Shock absorbers (hydraulic dampers) can then be made to stiffen or relax and heavy weights (mass dampers) can be moved to reduce oscillations in strong winds, or minimise damage in the event of an earthquake.
3. Buildings that detect an earthquake tremor could even warn other buildings nearby of the approach of a shockwave, so they could sound an alarm and prepare themselves accordingly.

SMART BRIDGE

1. Wireless sensors mounted on the bridge monitor vibrations, displacement and temperature. This information then "hops" across the network of sensor nodes to a central computer for analysis.
2. If a problem is detected, such as a loose bolt or cable, or the beginning of a crack, a warning can be sent by SMS.

SMART TUNNEL

1. Wireless sensors mounted on the walls of a tunnel monitor displacement, temperature and humidity. This information then "hops" across the network of sensor nodes to a central computer for analysis.
2. If a problem with the tunnel lining is detected, appropriate maintenance can be carried out. In future, a smart tunnel could even use robots to perform some maintenance tasks automatically.

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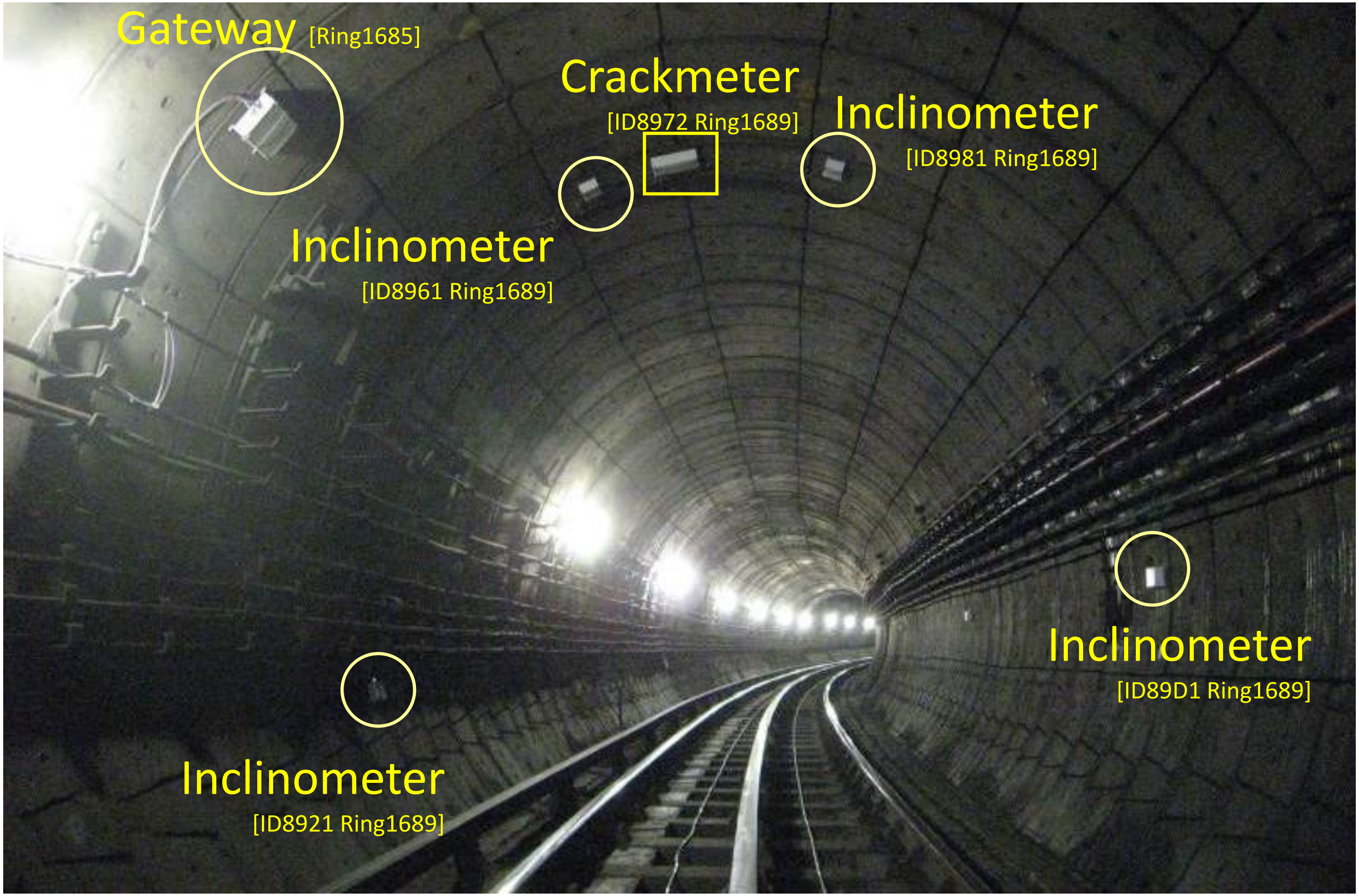
The Economist, December 2010

Wireless sensor networks in tunnels



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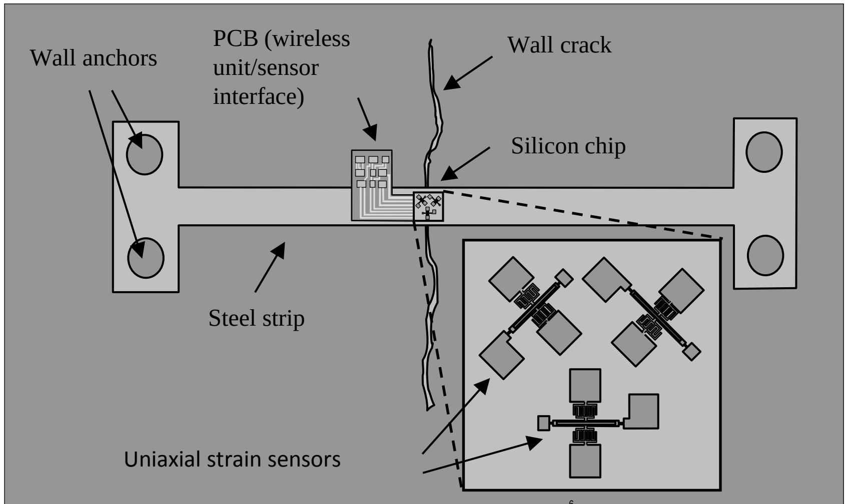
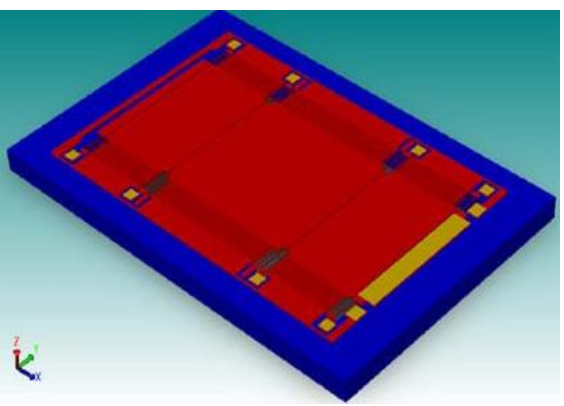
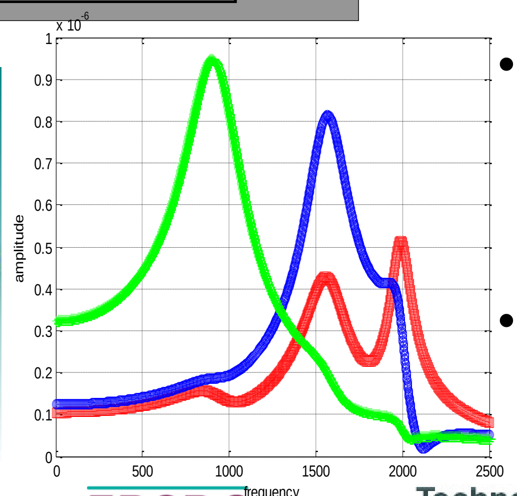
Energy harvesting for ultra-low power sensors







- Environmental sensors operating on scavenged energy.
- Sensor operating in remote areas or harsh environments.
- Augment batteries or extend battery life.
- Sensors embedded in low power distributed sensor networks for infrastructure monitoring.
- Energy harvesting from ambient mechanical, fluidic and thermal sources.

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Availability of ambient energy

Energy Source	Order of magnitude of potential power density
Solar (direct solar irradiation)	10's mW/cm^3
Solar (indoor illumination)	10's $\mu W/cm^3$
Mechanical vibration	100's $\mu W/cm^3$
Human motion	10's to 1,000's $\mu W/cm^3$
Thermoelectric	10's $\mu W/cm^2$
Temperature variation	1's $\mu W/cm^2$
Radio-frequency	100's nW/cm^3
Airflow	100's $\mu W/cm^3$
Acoustic noise	100's nW/cm^3

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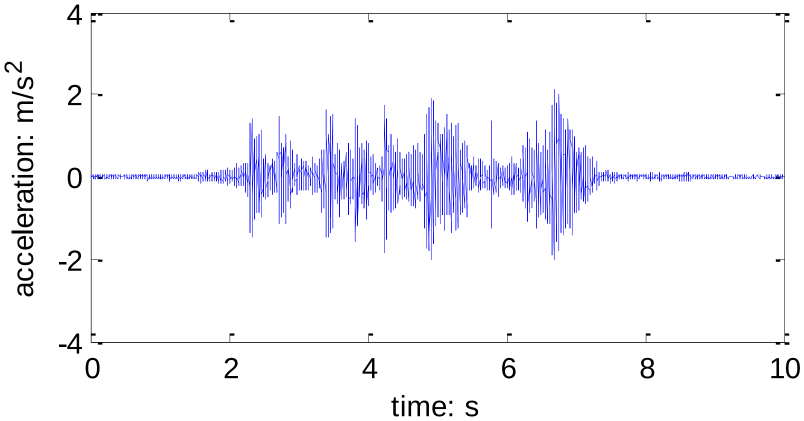
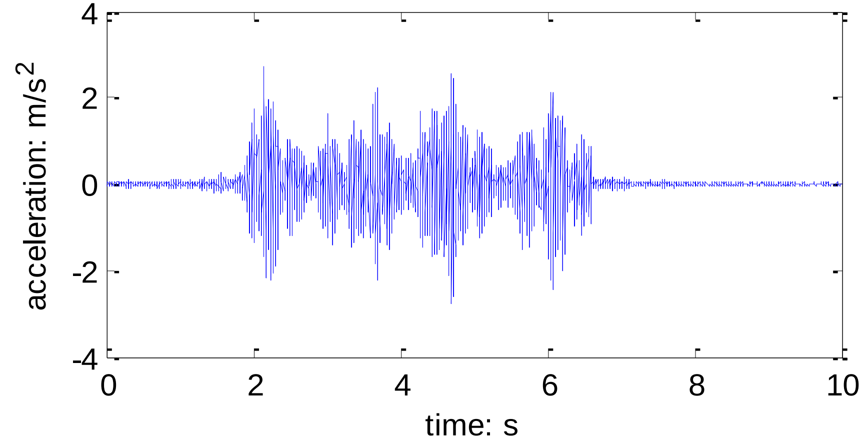
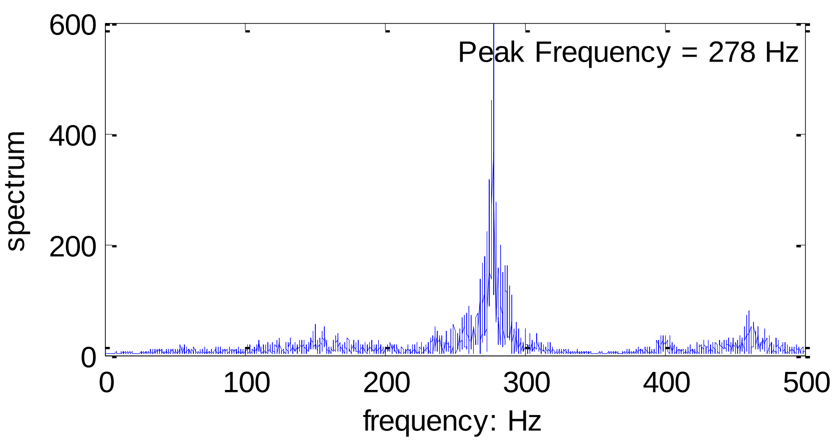
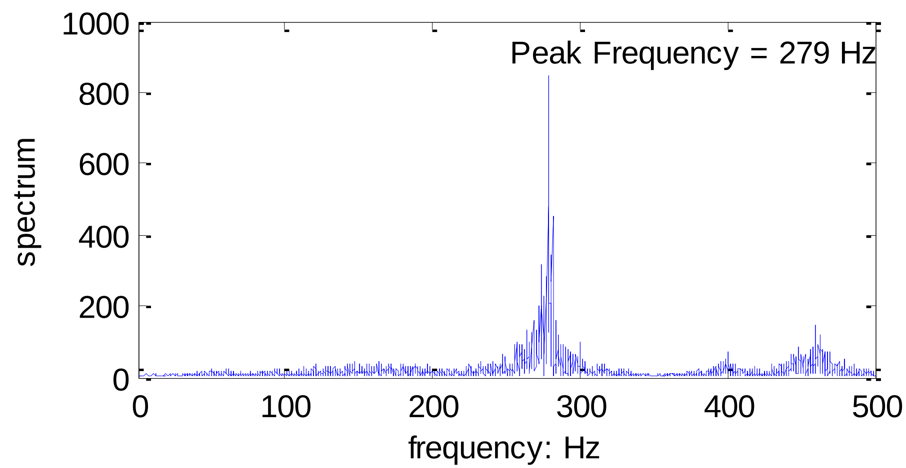
Ambient energy – rail track vibration









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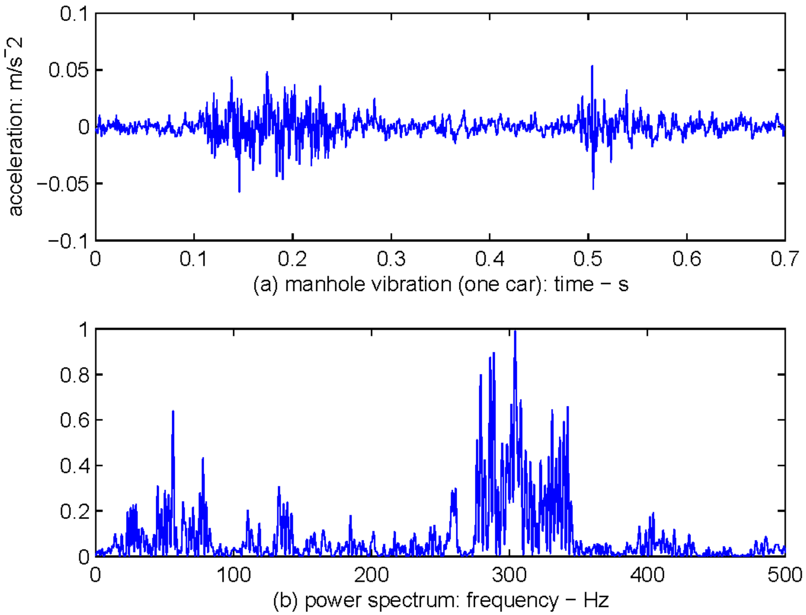
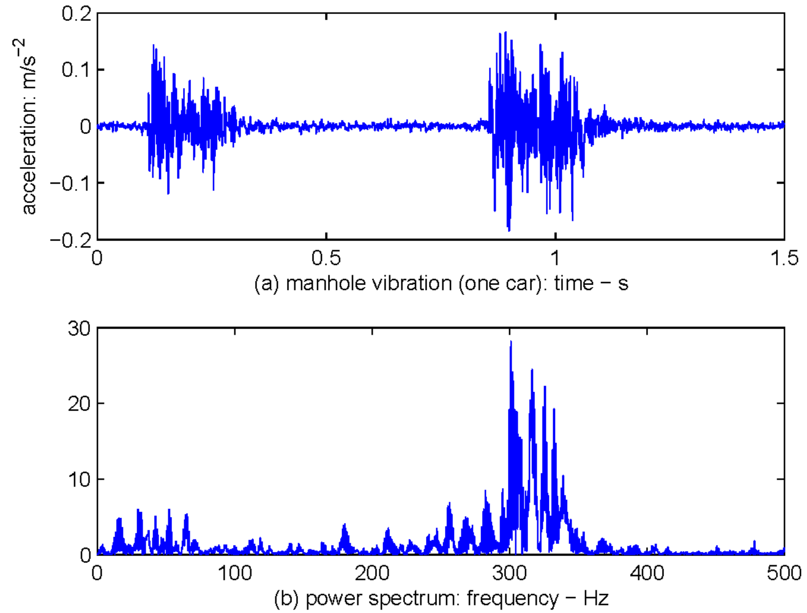
Ambient energy – pipeline monitoring





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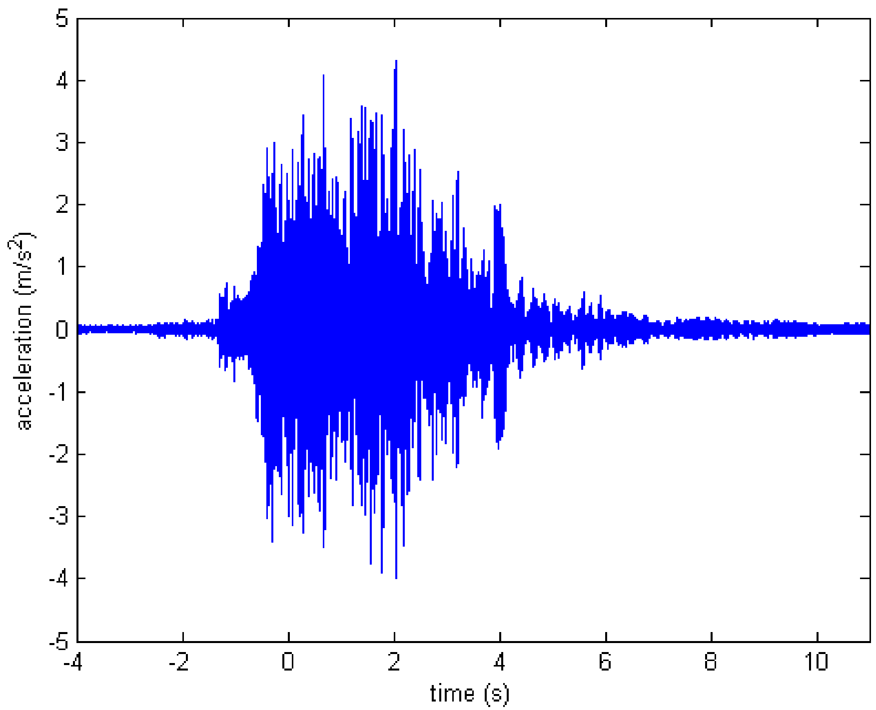
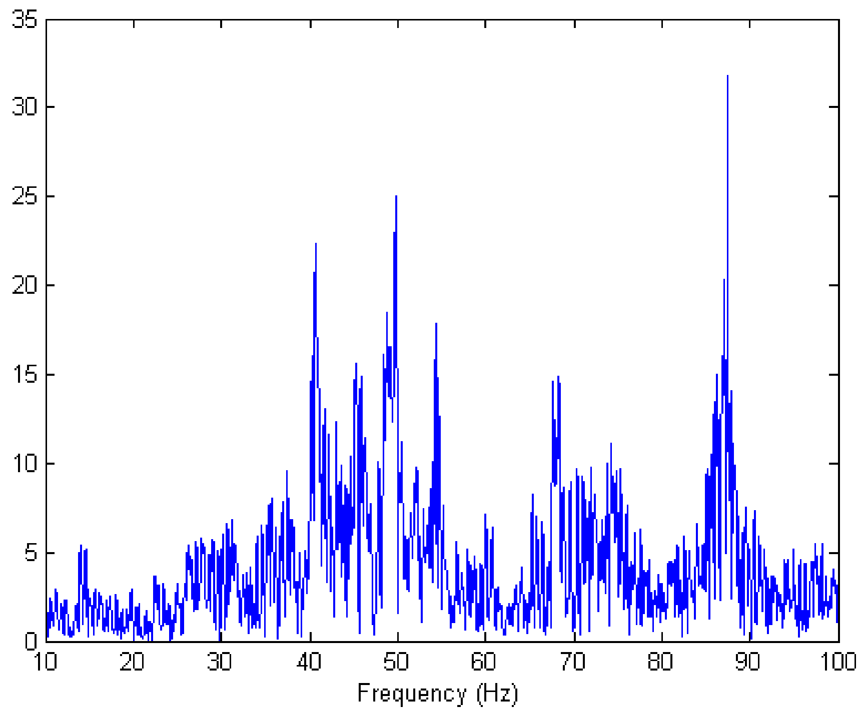
Real-world applications

- Intermittent, irregular and broadband nature of real vibrations.
- Arrayed linear, MDOF or non-linear approaches for vibration energy harvesting must be considered.
- Increased device complexity for non-linear mechanisms.





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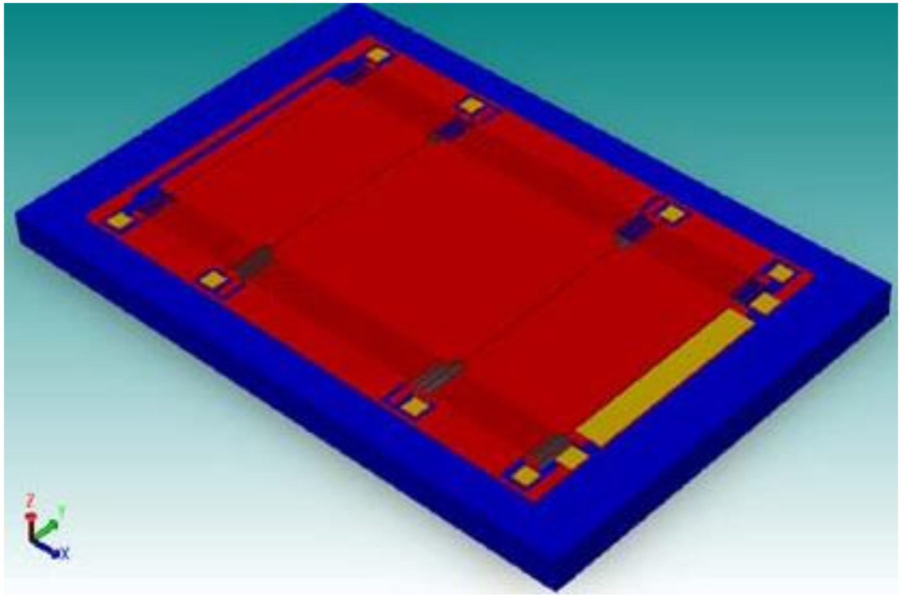
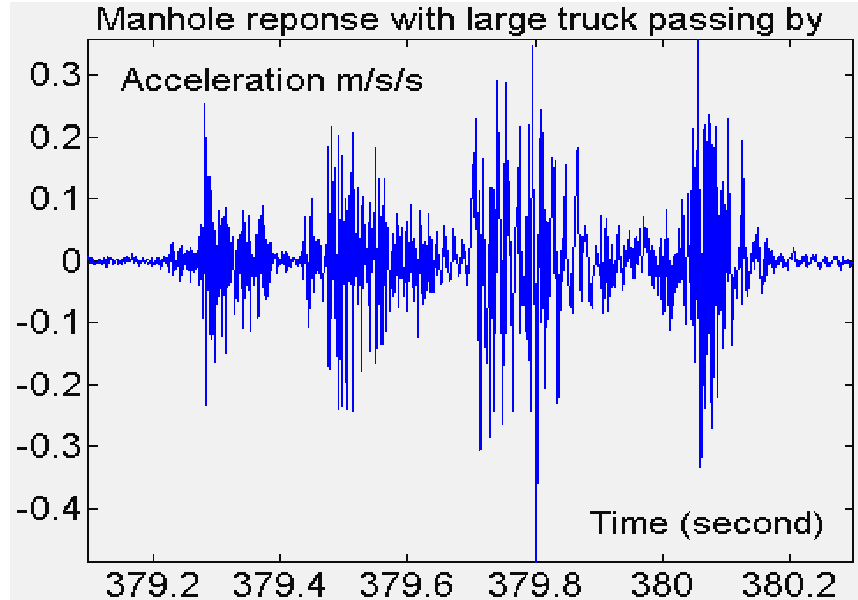
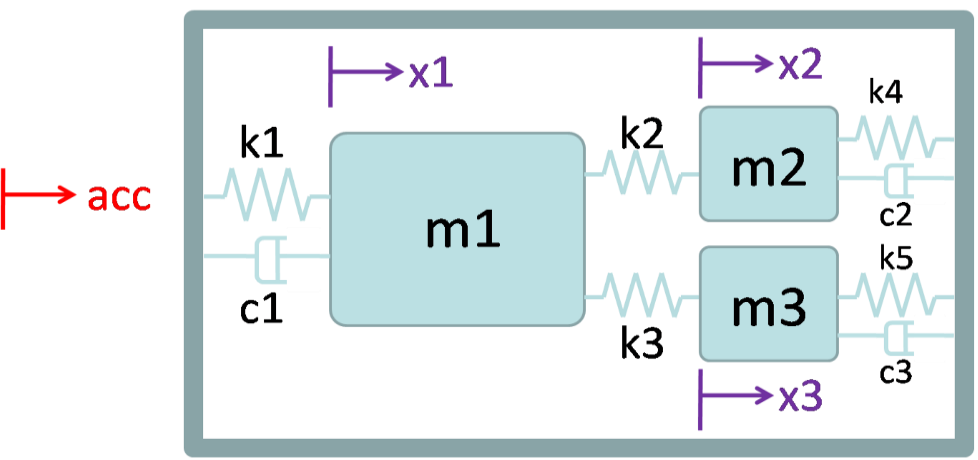
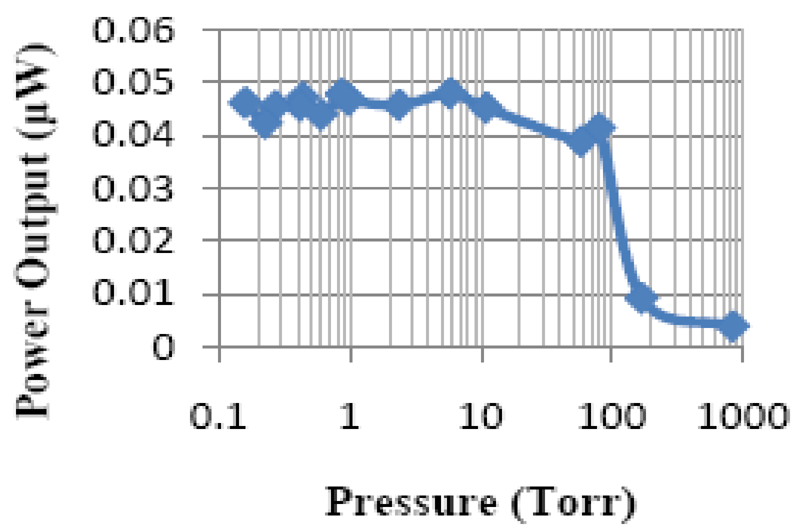
Energy Harvesting – MDOF MEMS approach





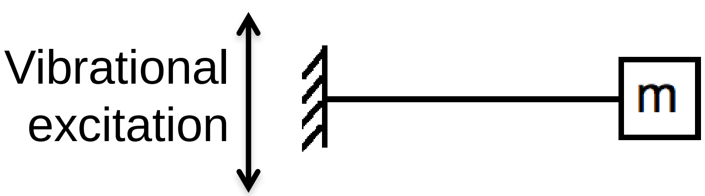


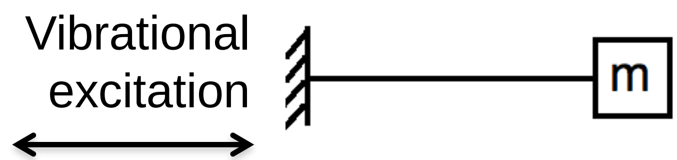


Z. J. Wong *et al*, *PowerMEMS* 2009.

Vibration Energy Harvesting

- Aims
  - Converting ambient vibration to useful energy
  - Self sustain low power wireless or remote systems
- Challenges
  - Limited power levels from conventional directly forced resonance
  - Confined frequency response despite broadband nature of real vibration





$$m\ddot{x}+c\dot{x}+kx+\mu x^3=F(t)$$

Direct resonance

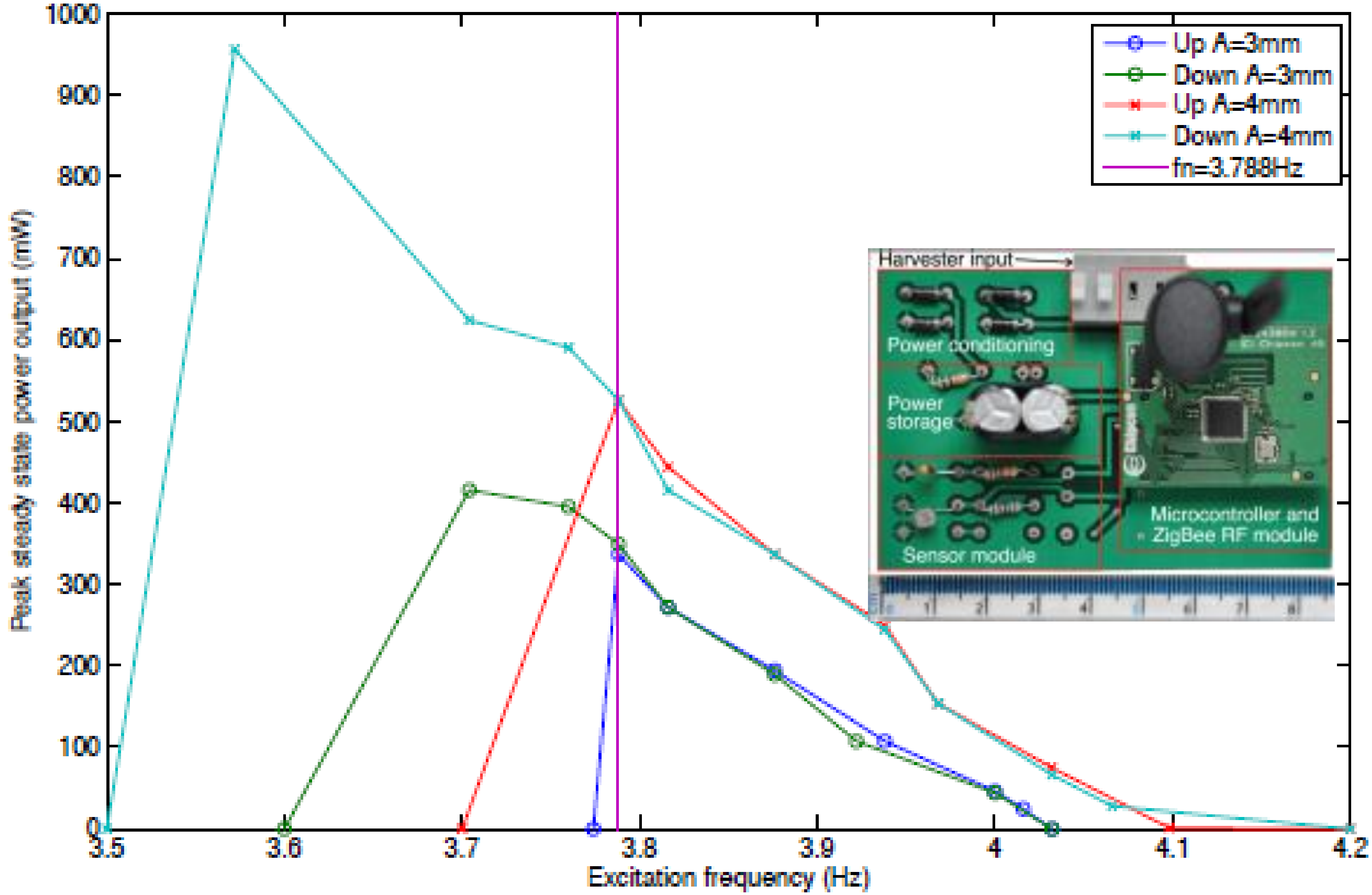
$$m\ddot{x}+c\dot{x}+k(t)x+\mu x^3=F(t)$$

Parametric resonance

Advantages of parametrically excited systems

- Stores an order more energy in the system: significantly improved mechanical-to-electrical transduction efficiency.
- Offers non-linear resonant peaks: this widens frequency band.
- Demonstrated:
  - 10x improvement in harvested power densities.
  - 3x improvement in the bandwidth for a given order of resonance.

Measured harvested energy



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Y. Jia *et al*, submitted to *Journal of Intelligent Materials Systems and Structures*, 2012 (under review).

Measured harvested energy

Reference	Peak power (mW)	Freq. (Hz)	Normalised Power Density ($\mu Wcm^{-3}m^{-2}s^4$)
PEVEH prototype	171.5	3.6	*293*
Perpetuum PMG-17 (2008)	1.000	100	119
Lumedyne Technologies (2008)	1.000	53	37
Ferro Solutions VEH-460 (2009)	5.270	60	32.3
Waters (2008)	18.00	90	6.93
Glynne-Jones (2001)	2.800	106	4.53

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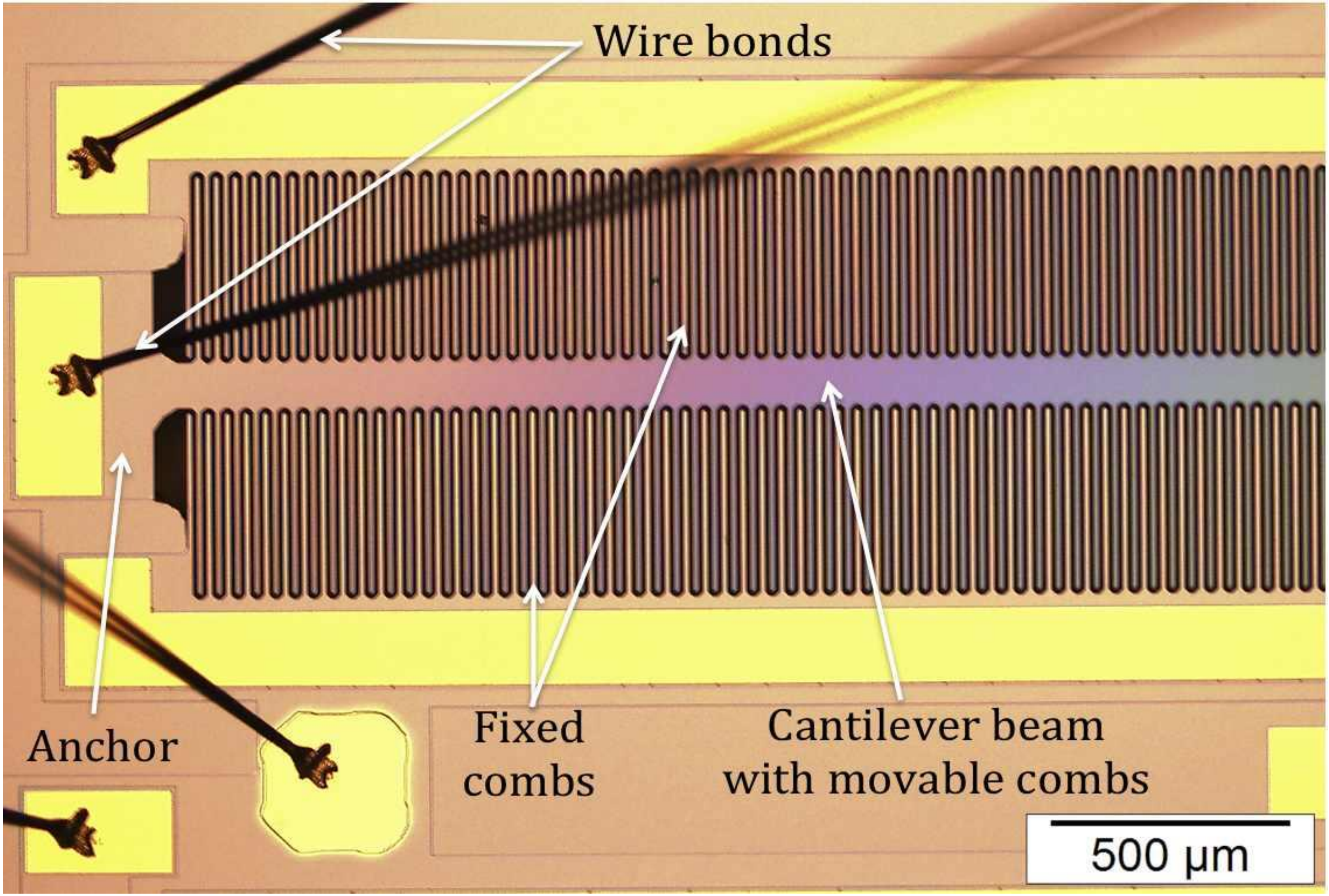
MEMS parametric harvester



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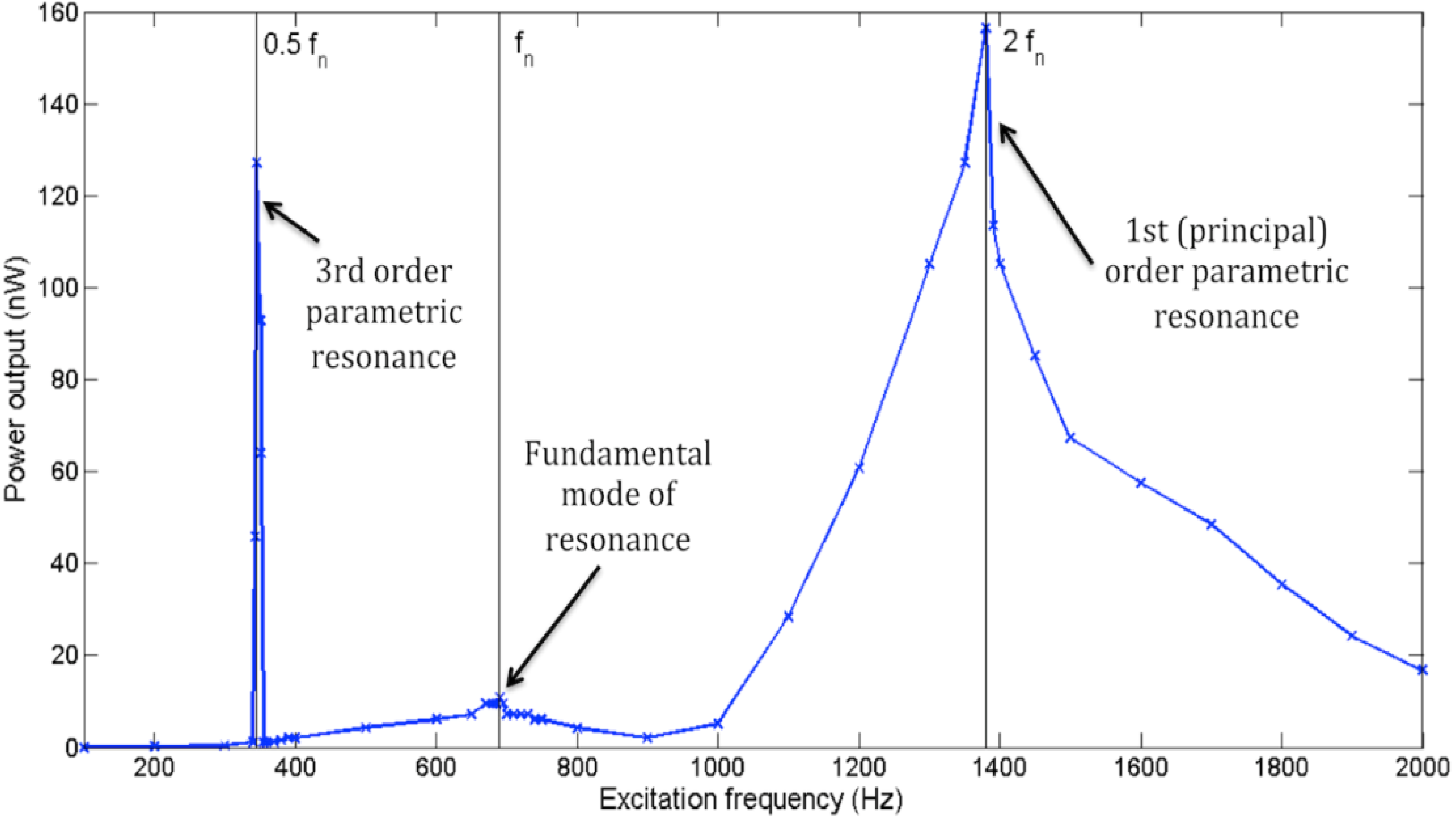
Y. Jia *et al*, *PowerMEMS* 2012.

MEMS parametric harvester



Y. Jia *et al*, *PowerMEMS* 2012.

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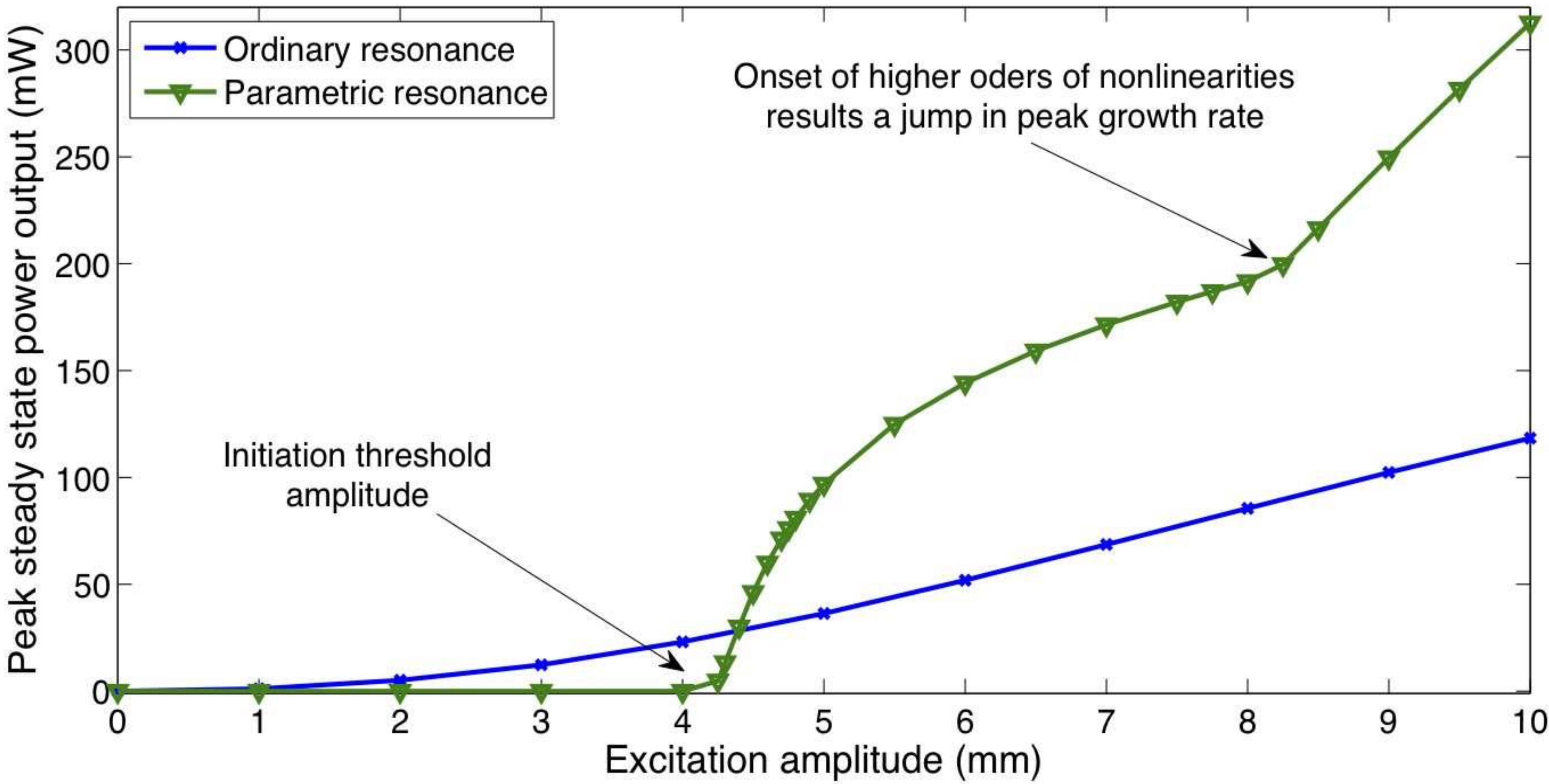
The problem of initiation threshold amplitude



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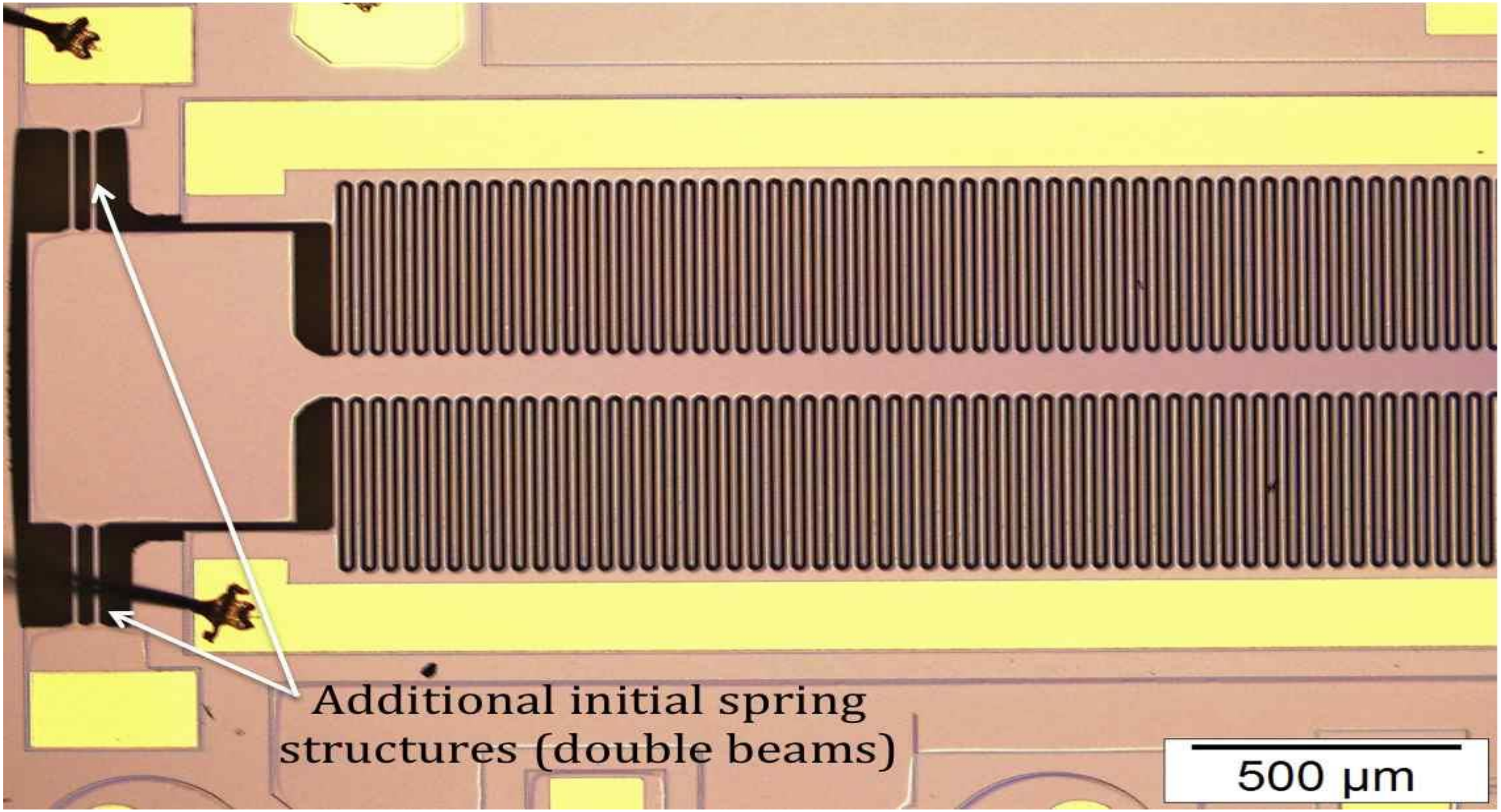
MEMS auto-parametric harvesters



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Y. Jia *et al*, *PowerMEMS* 2012.

MEMS vibration energy harvesters

Reference	Power (μW)	Acc. ($\mathrm{ms^{-2}}$)	Freq. (Hz)	Index ($\mu\mathrm{W cm^{-3} m^{-2} s^4}$)
Parametric (1st order)	0.156	4.2	1380	*60.2*
Parametric (3rd order)	0.127	4.2	342.5	*49.0*
Despesse *et al.* (2005) [11]	70	9.2	50	25.5
Roundy *et al.* (2002) [2]	116	2.25	120	22.9
Wong *et al.* (2009) [10]	0.017	1.76	1400	17.2
Fundamental mode	0.011	4.2	700	*4.24*
Chu *et al.* (2005) [12]	32.34	40	800	1.01

Summary

- Structural health monitoring in the context of ageing civil infrastructures is an emerging application area for large-scale distributed sensors and sensor networks.
- Ambient vibrations provide a potentially promising energy source for autonomous sensors and sensor networks.
    - Broadband, intermittent and irregular nature of real vibrations.
- Approaches to vibration energy harvesting based on time-varying, non-linear or stochastic processes provide a potentially interesting route to design evolution for vibration energy harvesting.
- A parametrically excited vibration energy harvesting technology has been developed in our group providing the potential for-
    - Significantly enhanced power output densities.
    - Increased bandwidth of operation.
- Future work in our group is addressing the integration of macro-scale vibration energy harvesters with wireless sensor modules for field deployment and the continued development of MEMS-based and other complementary energy harvesting approaches.

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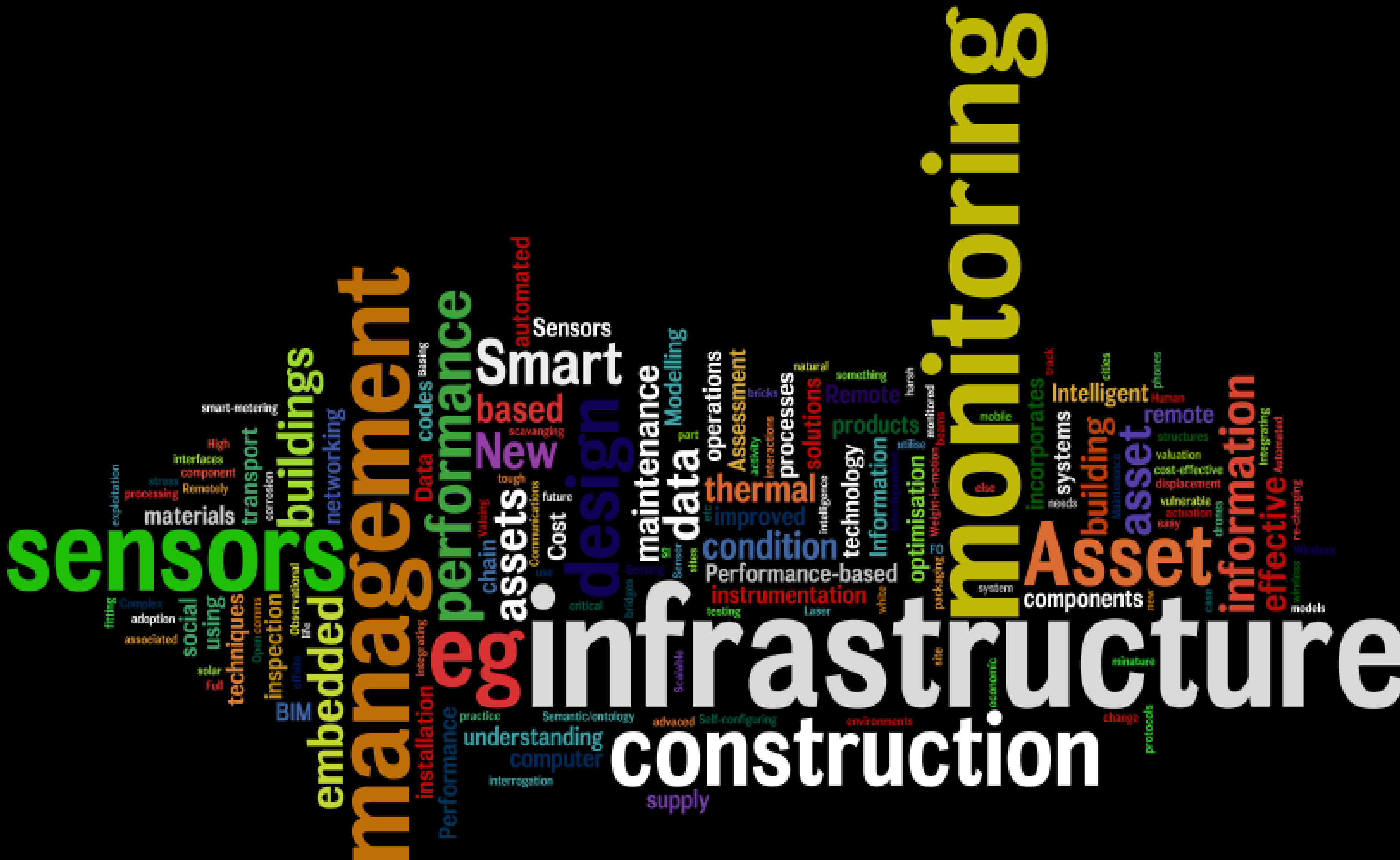

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