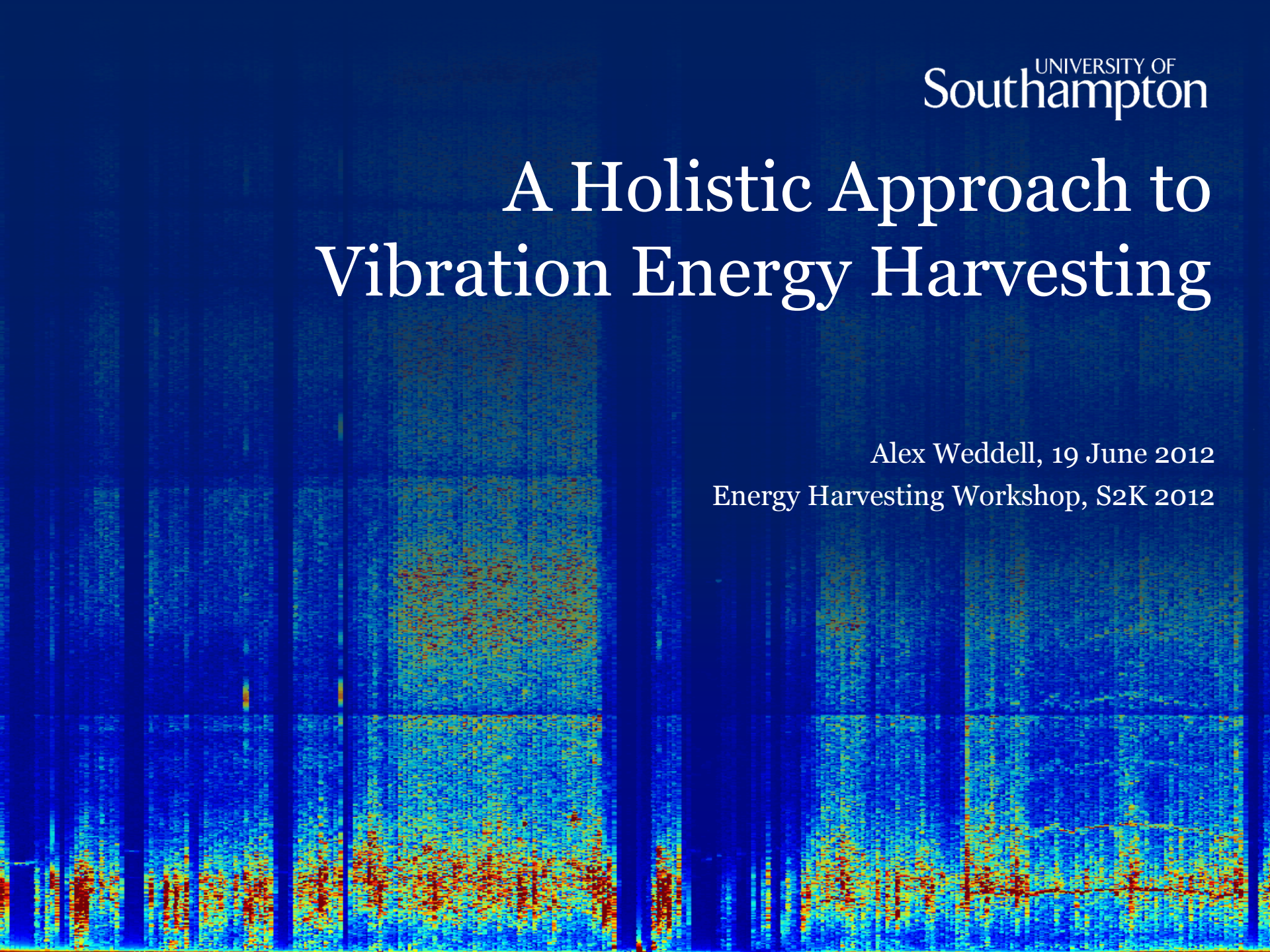


UNIVERSITY OF Southampton

A Holistic Approach to Vibration Energy Harvesting

Alex Weddell, 19 June 2012

Energy Harvesting Workshop, S2K 2012

Overview

- **Applications of Vibration Energy Harvesting**
- **Real Vibration Data**
- **Holistic Design of Energy Harvesting Systems**
- **Accelerated Simulation**
- **Case Study: Ferry Engine**
- **Contributions from Project Partners**
- **The Energy Harvesting Network**

holistic
energy harvesting

Applications of Vibration EH

- Typically condition monitoring, using wireless sensors
  - Sensors can be retro-fitted without electrician/batteries

- Also applications in asset tracking, monitoring of rotating machinery, even human health monitoring

Energy Harvesting used for Wireless Condition Monitoring, *GE* [Online]. Available: http://eh-network.org/events/dissemination2011/presentations/Tom%20Berry.pdf

Limitations of Vibration EH

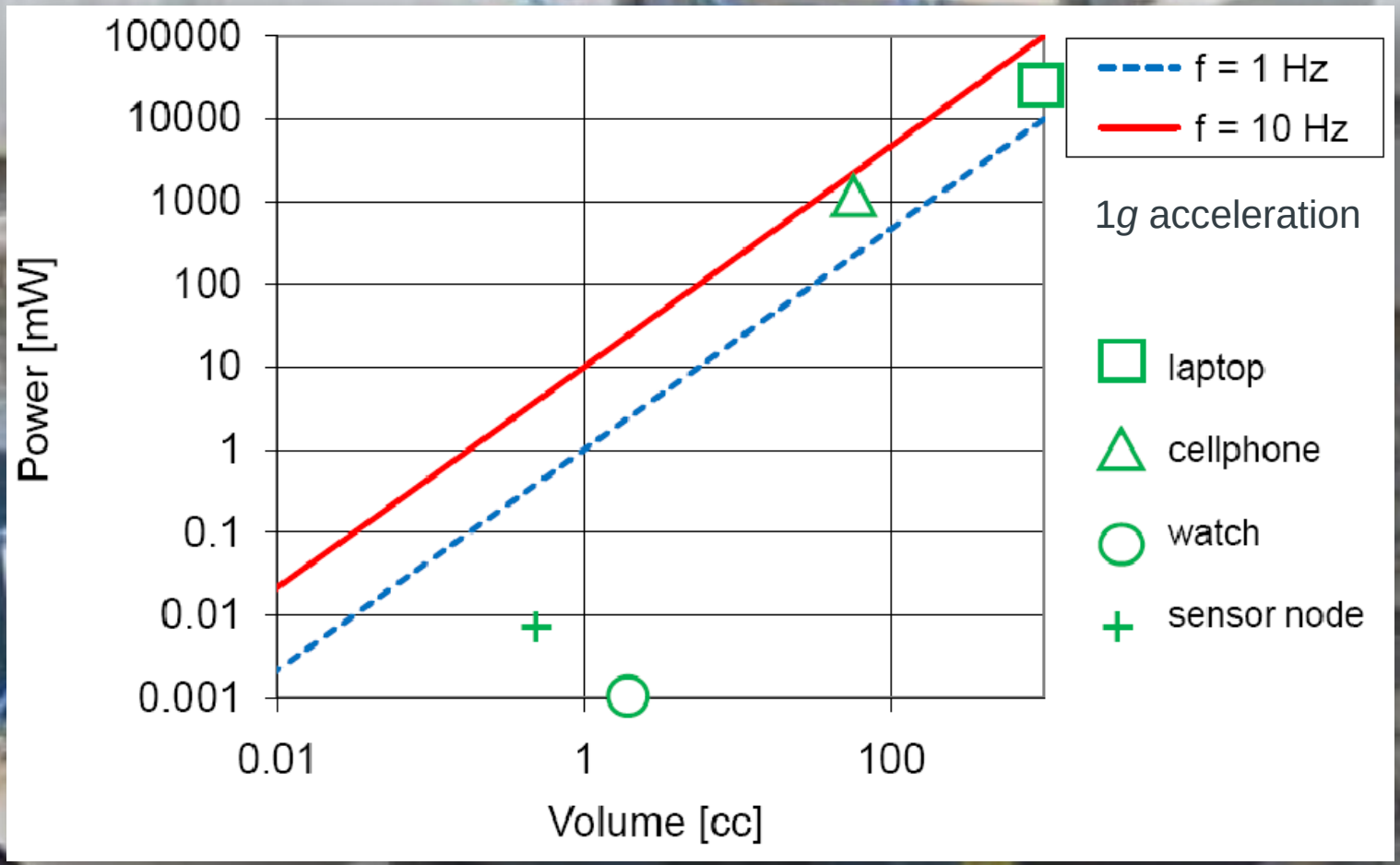
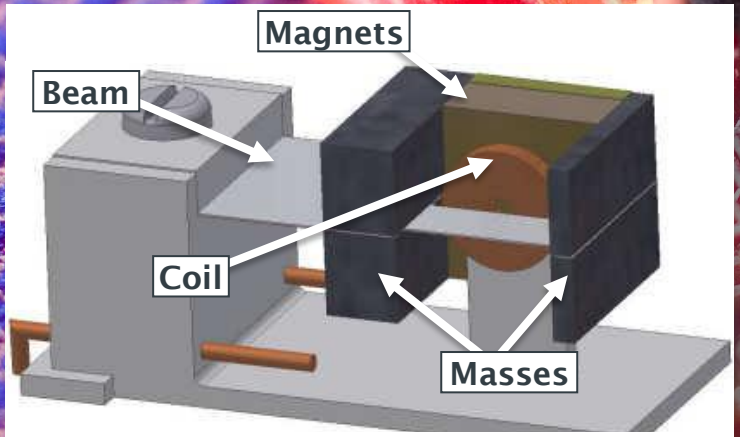


Image: P. Mitcheson, "Next Generation Energy-Harvesting Electronics " [Online], available: http://www.holistic.ecs.soton.ac.uk/presentations/mitcheson_npl.pdf

Starting Point

An energy-aware wireless condition monitoring sensor node powered by very low vibration levels, $0.02ms^{-2}_{rms}$.

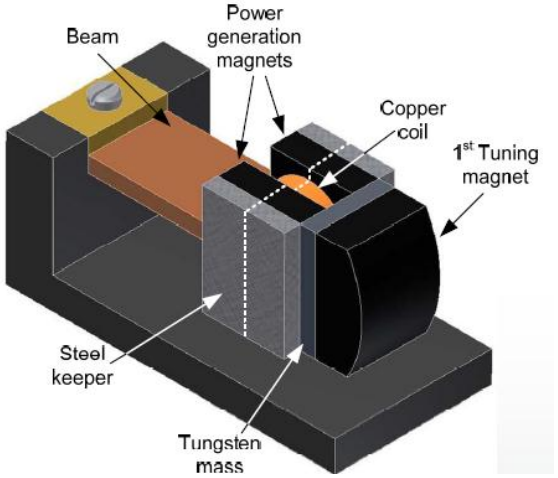


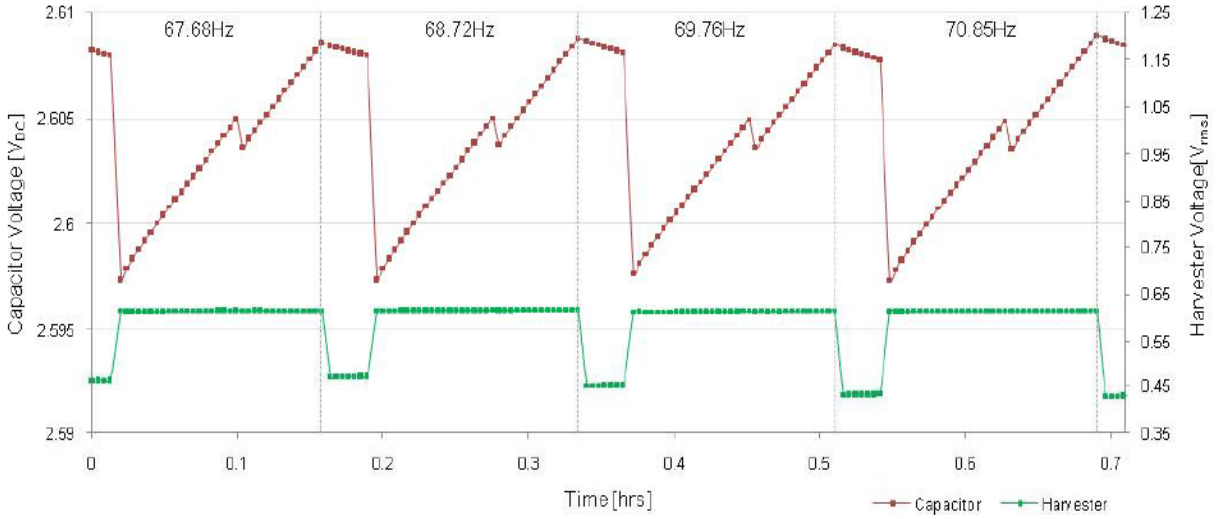
Cutaway of the Electromagnetic Micro-generator, optimal power output of $58\mu Wrms$ @ $0.06ms^{-2}$.

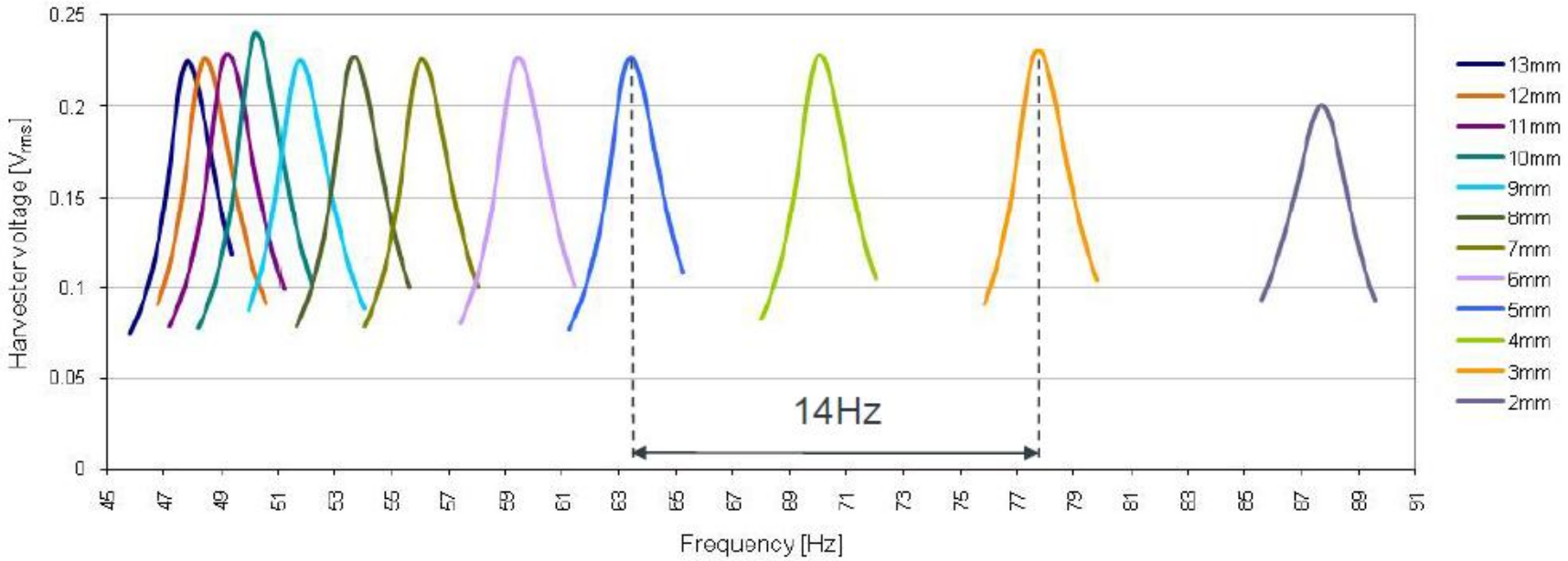
30mm

Torah, R., Glynne-Jones, P., Tudor, J., O'Donnell, T., Roy, S. and Beeby, S. (2008) Self-powered autonomous wireless sensor node using vibration energy harvesting. Measurement Science and Technology, 19 (12). ISSN 1361-6501

Southampton Tuneable Generator





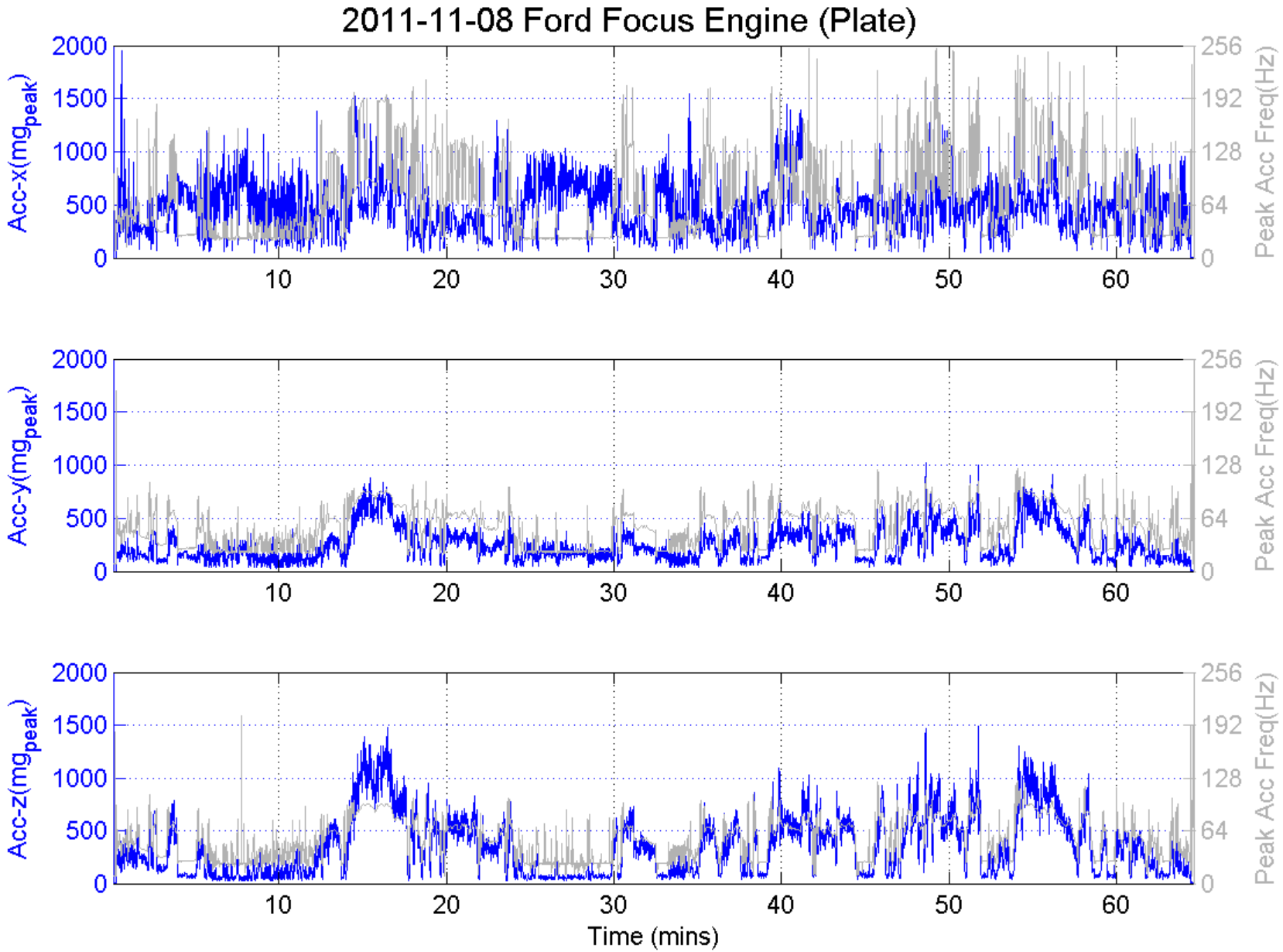


Zhu, Dibin, Roberts, Stephen, Tudor, John and Beeby, Steve (2010) Design and experimental characterization of a tunable vibration-based electromagnetic micro-generator. Sensors and Actuators A, 158, (2), 284-293.

Harvesters are usually tuned to a fixed frequency.

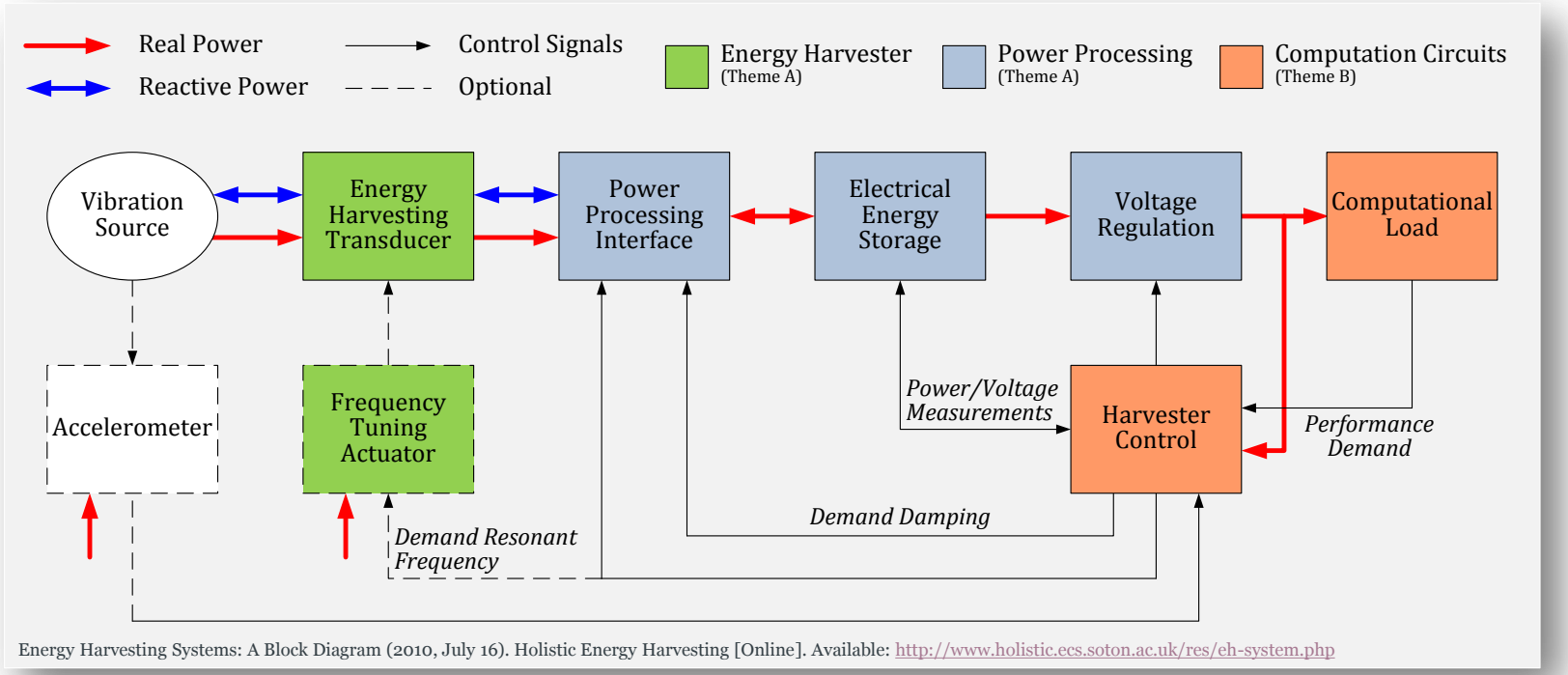
Many real-life vibration sources vary temporally and spatially in frequency and amplitude.

Adaptive generators *and* sensor systems are required


2011-11-08 Ford Focus Engine (Plate)
Acc-x(mg_peak)
Acc-y(mg_peak)
Acc-z(mg_peak)
Peak Acc Freq(Hz)
0
500
1000
1500
2000
64
128
192
256
10
20
30
40
50
60
Time (mins)
FFT interval 1s FFT length 1s Sample Rate 1024Hz Duration 3880s

Holistic Design of EH Systems

- Design sub-systems, define interfaces, plug them together
- Few have considered interactions in the entire system.
- How do we design and model systems containing mechanics, circuits, devices, computation and algorithms?



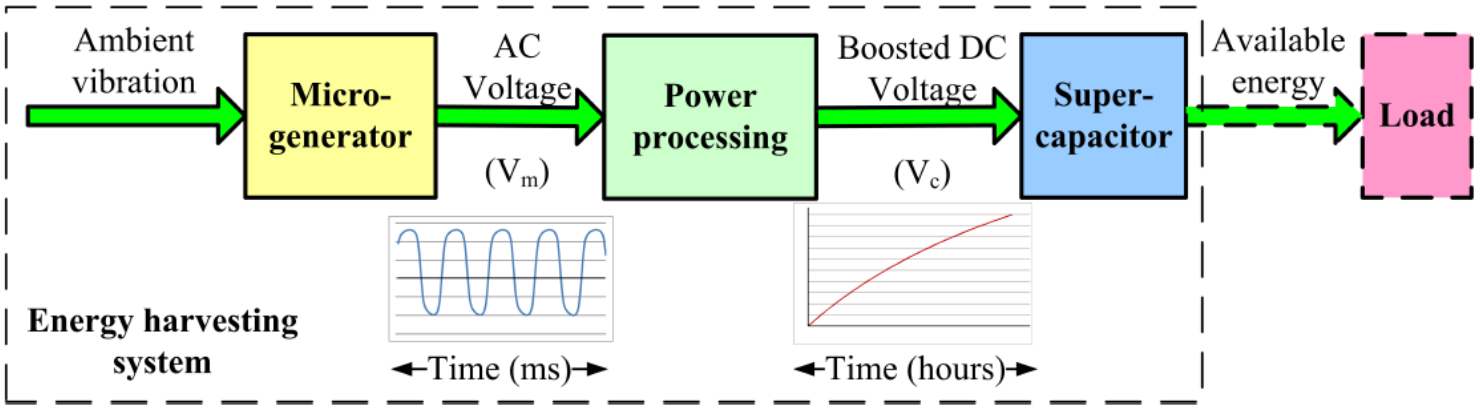
Energy Harvesting Systems: A Block Diagram (2010, July 16). Holistic Energy Harvesting [Online]. Available: http://www.holistic.ecs.soton.ac.uk/res/eh-system.php

http://www.holistic.ecs.soton.ac.uk/

holistic energy harvesting

Simulation and Optimisation

- EH-nodes are complex and hard to simulate



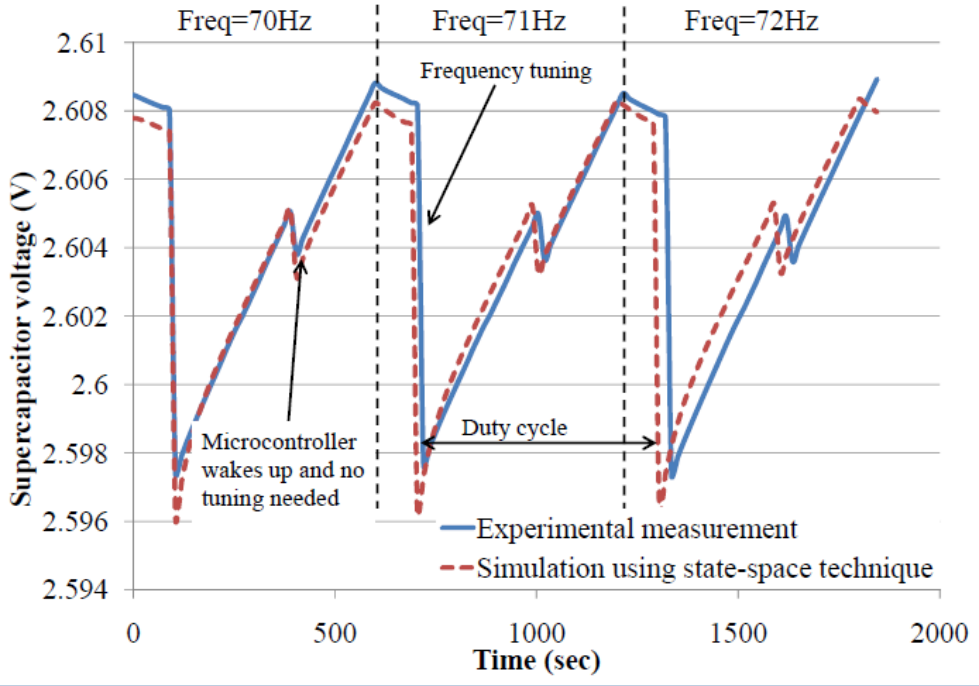
- Mix of long and short time-constants
  - Disparity between vibration (ms) & storage (hrs)

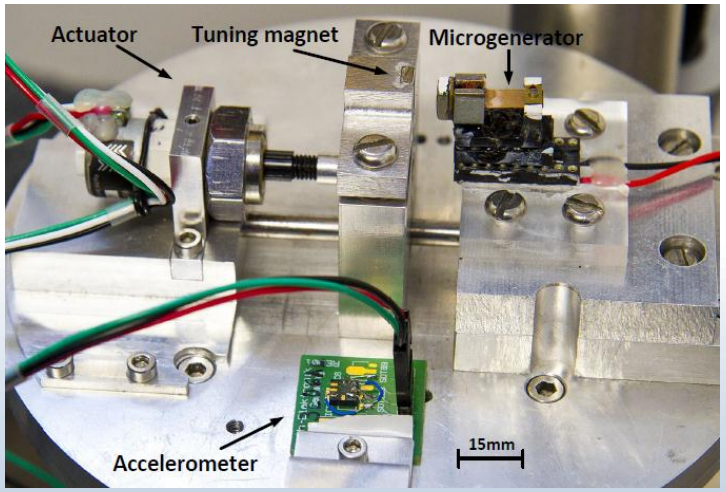
Simulation of the supercapacitor charging curve of an energy harvester			
Simulator	SystemVision (VHDL-AMS)	OrCAD (PSPICE)	Visual C++ (SystemC-A)
CPU time (P4, 2G RAM)	4h 24min	9h 48min	6h 40min

Wang, Leran, Kazmierski, Tom, Al-Hashimi, Bashir, Weddell, Alex, Merrett, Geoff and Ayala Garcia, Ivo (2011) Accelerated simulation of tunable vibration energy harvesting systems using a linearised state-space technique. In, Design, Test and Automation in Europe (DATE 2011), Grenoble, France, 14 - 18 Mar 2011.

Increasing Simulation Speed

- Able to simulate complete tuneable EH systems
  - New simulation technique: accurate and 100x faster
  - Permits system optimisation, and potentially synthesis



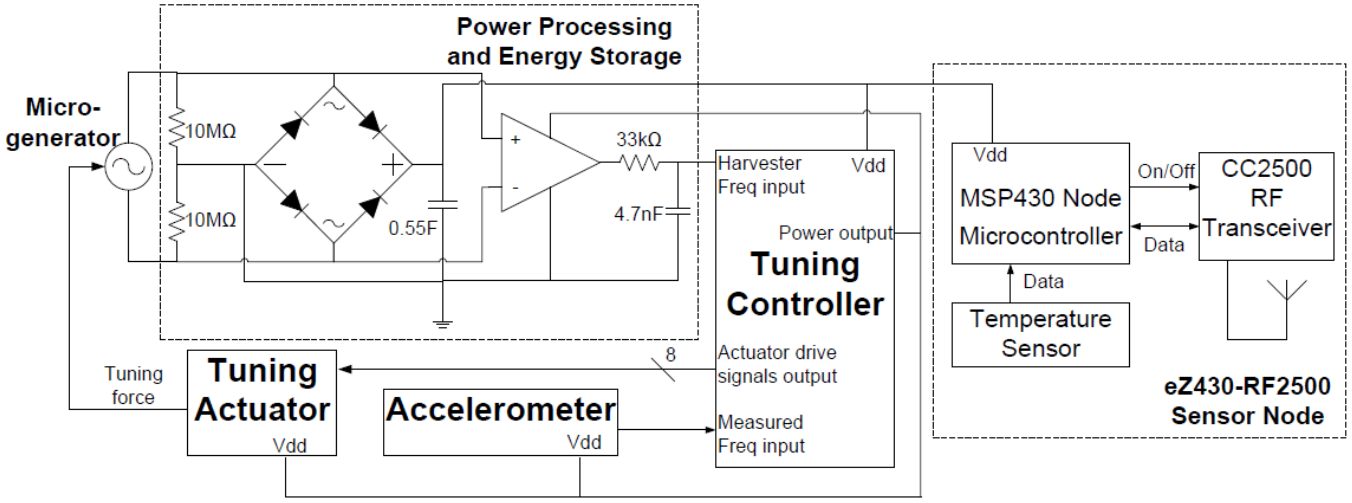


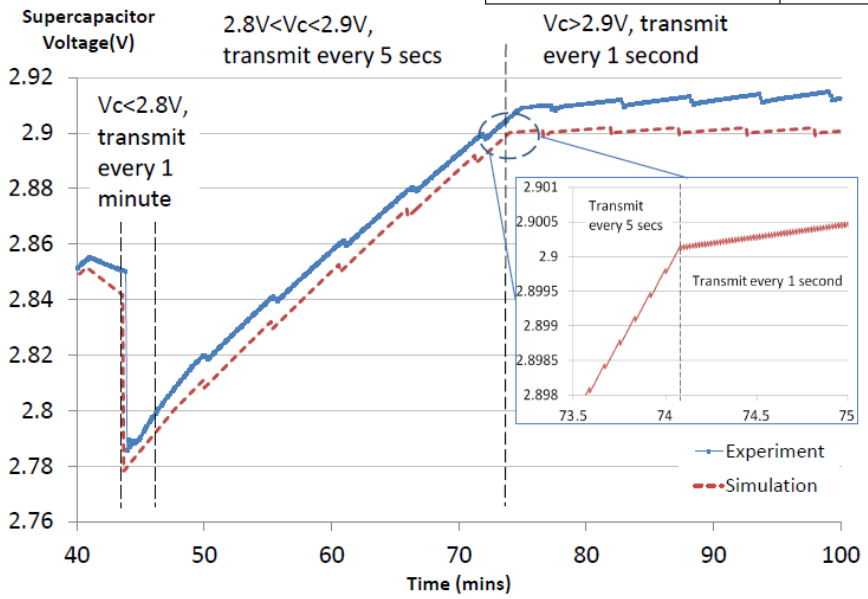
	Existing technique		Proposed technique
Integration method	Implicit Newton-Raphson based		Explicit linearized Adams-Bashforth
HDL	VHDL-AMS	SystemC-A	
Scenario 1	2448 sec	3155 sec	23.3 sec

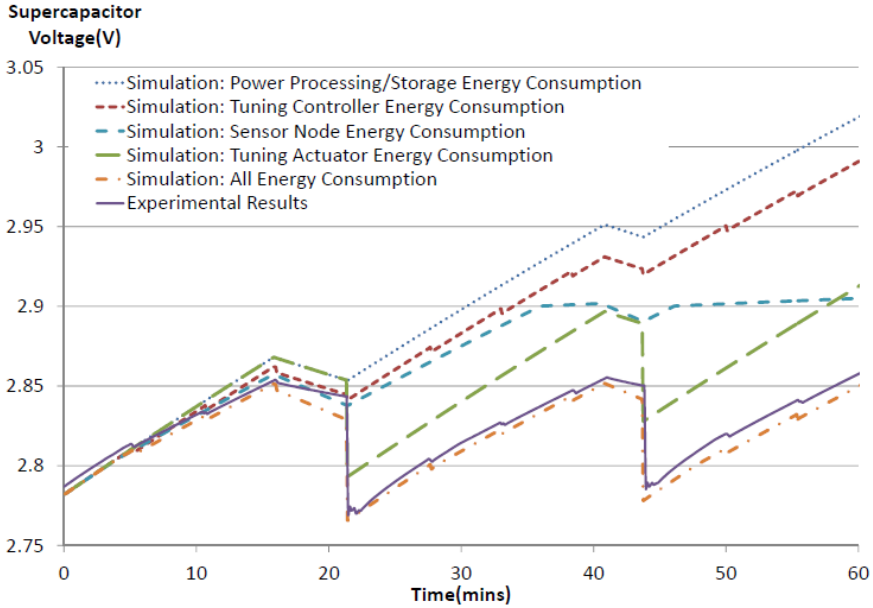
Download: Holistic Energy Harvesting Simulation Toolkit, http://www.holistic.ecs.soton.ac.uk/resources.php

L. Wang, T.J. Kazmierski, B.M. Al-Hashimi, A.S. Weddell, G.V. Merrett, I.A Garcia, "Accelerated simulation of tunable vibration energy harvesting systems using a linearised state-space technique. In, Design, Test and Automation in Europe (DATE 2011), Grenoble, France, 14 - 18 Mar 2011.

Simulating EH-WSN*odes*



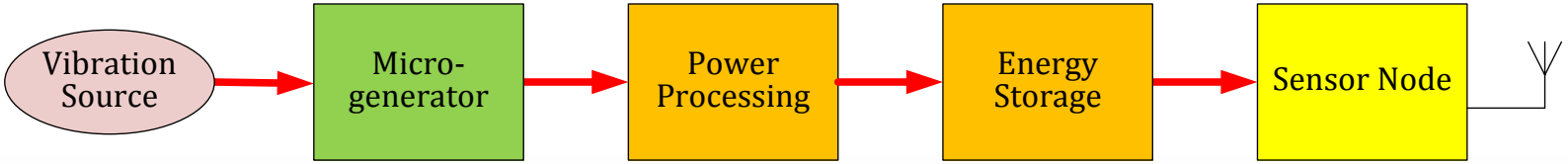




Kazmierski, Tom, Merrett, Geoff V., Wang, Leran, Al-Hashimi, Bashir, Weddell, Alex S. and Ayala Garcia, Ivo (2012) Modeling of Wireless Sensor Nodes Powered by Tunable Energy Harvesters: HDL-Based Approach. IEEE Sensors Journal (In Press)

EH-WSN Design Explorer

- Ability to explore a design in real-time
  - Energy-aware node, simulated for 10 hours



- 8 parameters
- 4 circuits
- 6 performance indicators
- RSM built from 180 simulations

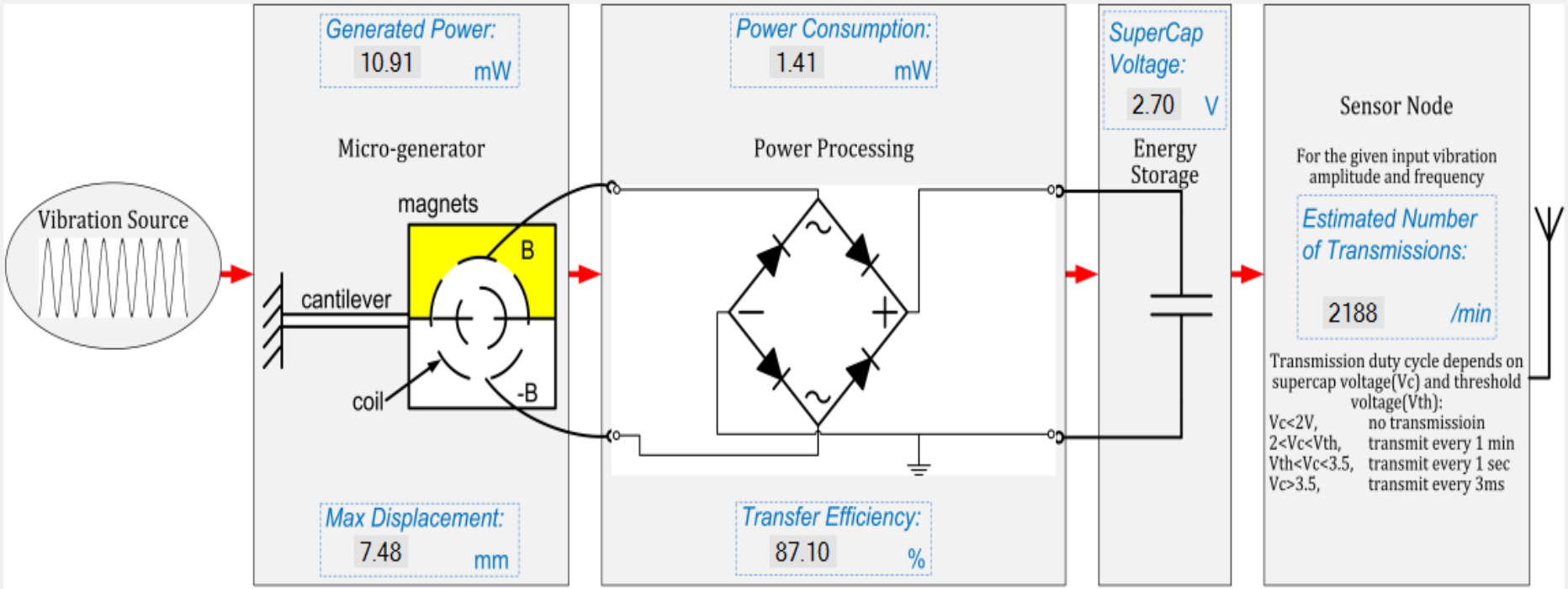
	Vibration source	Micro-generator	Power processing	Storage	Sensor node
User parameters	Amplitude of sine wave	Proof mass	Diode bridge rectifier	Super-capacitor value	Threshold when transmission frequency changes
		Stiffness of cantilever	3-stage VM		
	Frequency of sine wave	Number of coil turns	4-stage VM		
		Mechanical Q factor	5-stage VM		
Performance indicators		Generated power	Power consumption	Super-capacitor voltage	Number of transmissions
		Maximum displacement	Transfer efficiency		

RSM Design Explorer

File Edit Help

Performance estimator of wireless sensor powered by kinetic energy harvester

Back



User parameters

Peak Amp: 700 mg (100~1000mg)

Freq: 50.00 Hz (50~250Hz)

Proof mass: (2~12g) 2.0 g

Number of coil turns: (500~5000) 2000

Mechanical Q: (100~500) 200

Cantilever
- Length: 10.00 mm
- Width: 2.00 mm
- Thickness: 150.0 um
- Material: Copper

Diode bridge
3-stage voltage multiplier
4-stage voltage multiplier
5-stage voltage multiplier

Resonant Frequency: 50.01 Hz

Operating Freq Range: 49.750 to 50.250 Hz

Super-capacitor value (0.1~1F): 0.55 F

Energy consumption per transmission(10~1000uJ): 116.0 uJ

SuperCap threshold voltage (2.5~3V): 2.50 V

The resonant frequency of cantilever is close to the input frequency.
Performance indicators updated.

Engine Condition Monitoring

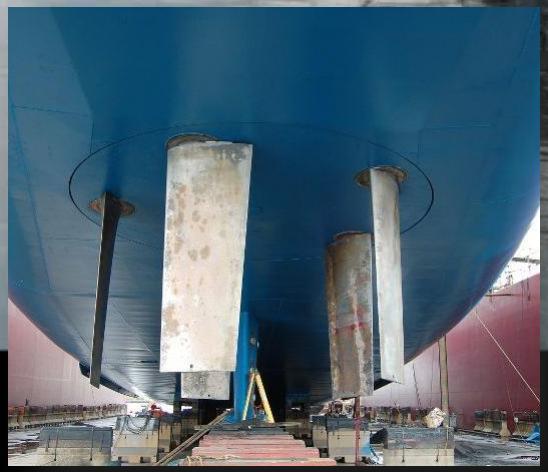
Engine Speeds

Idle (350RPM)

Slow (550RPM)

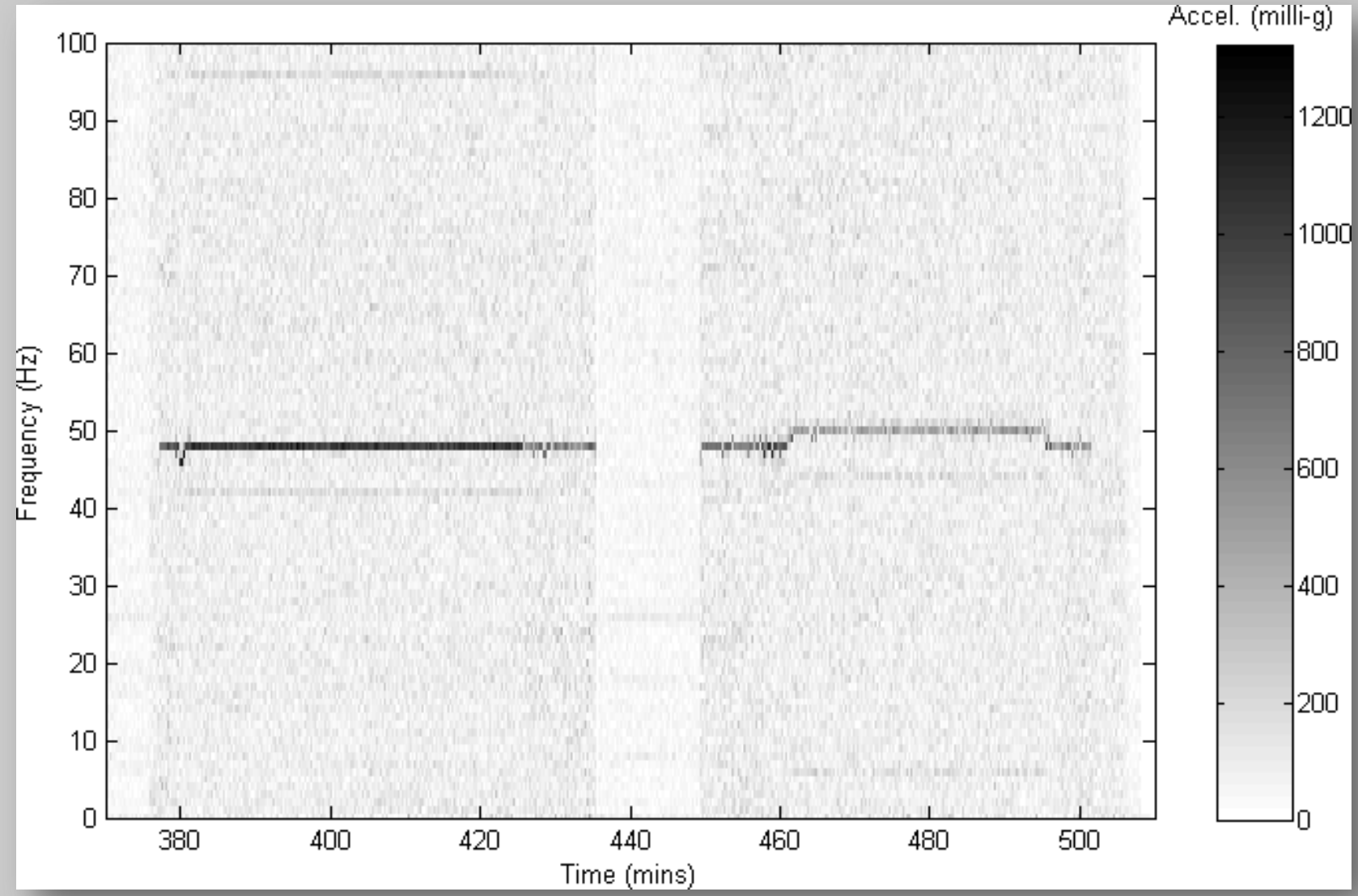
Normal (715RPM)

Fast (750RPM)



http://www.imcbrokers.com/blog/overview/p/detail/propulsion-voith-schneider

Acceleration Data



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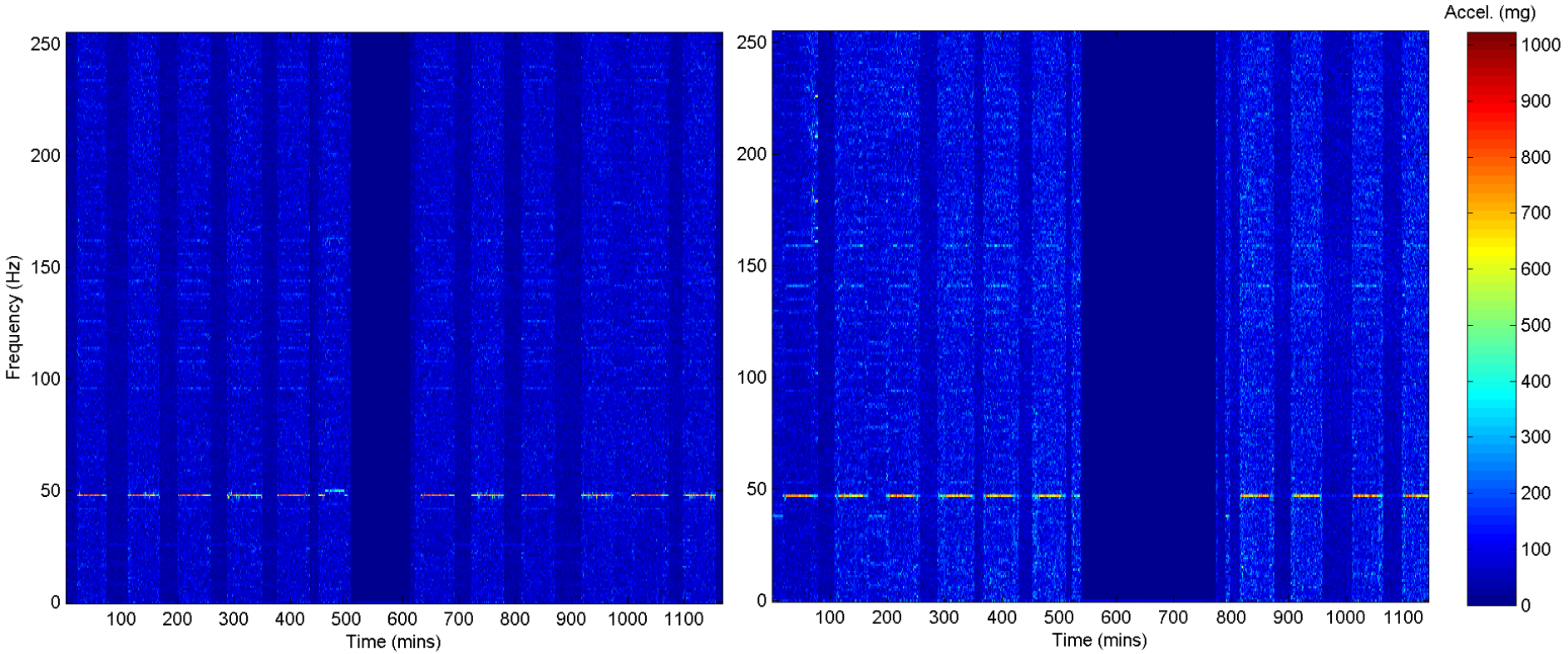
Long-Term Tests on Two Ferries

- Is the vibration signature similar on
  - different crossings, and
  - different ferries?



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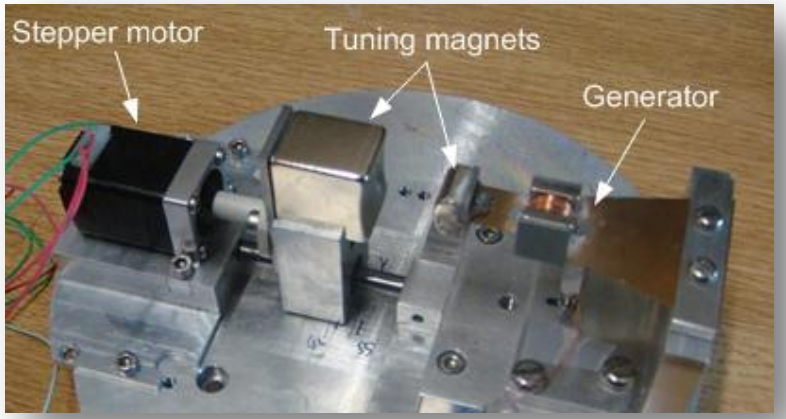
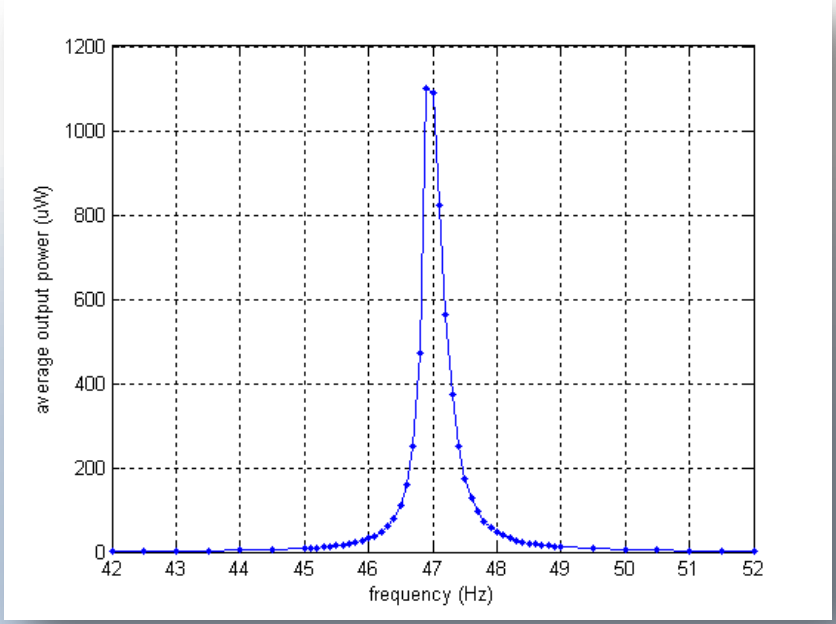
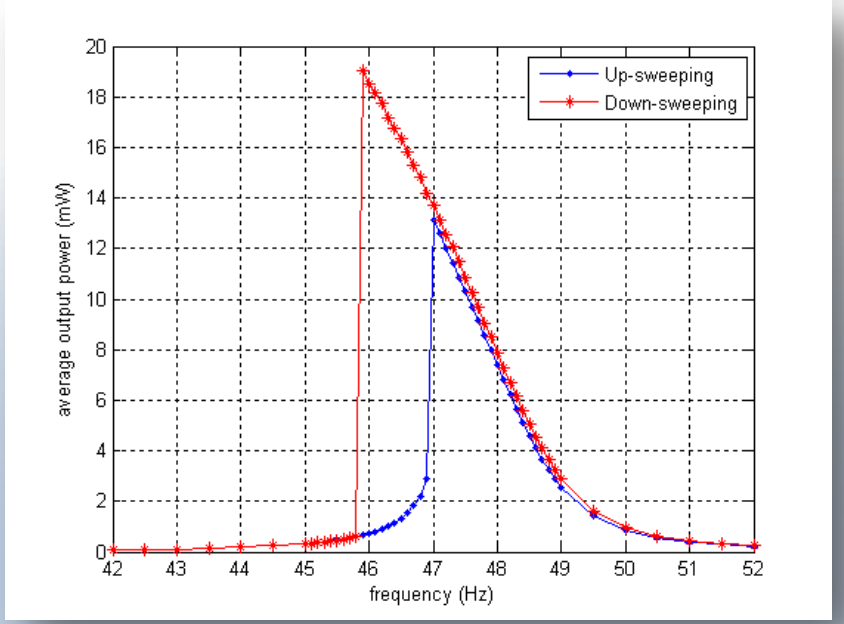
Tuneable Generator

- Specification
  - Frequency range: 42-55Hz
  - Max Amplitude 1 'g'







Power: 100mg$_{peak}$, generator tuned to 47Hz

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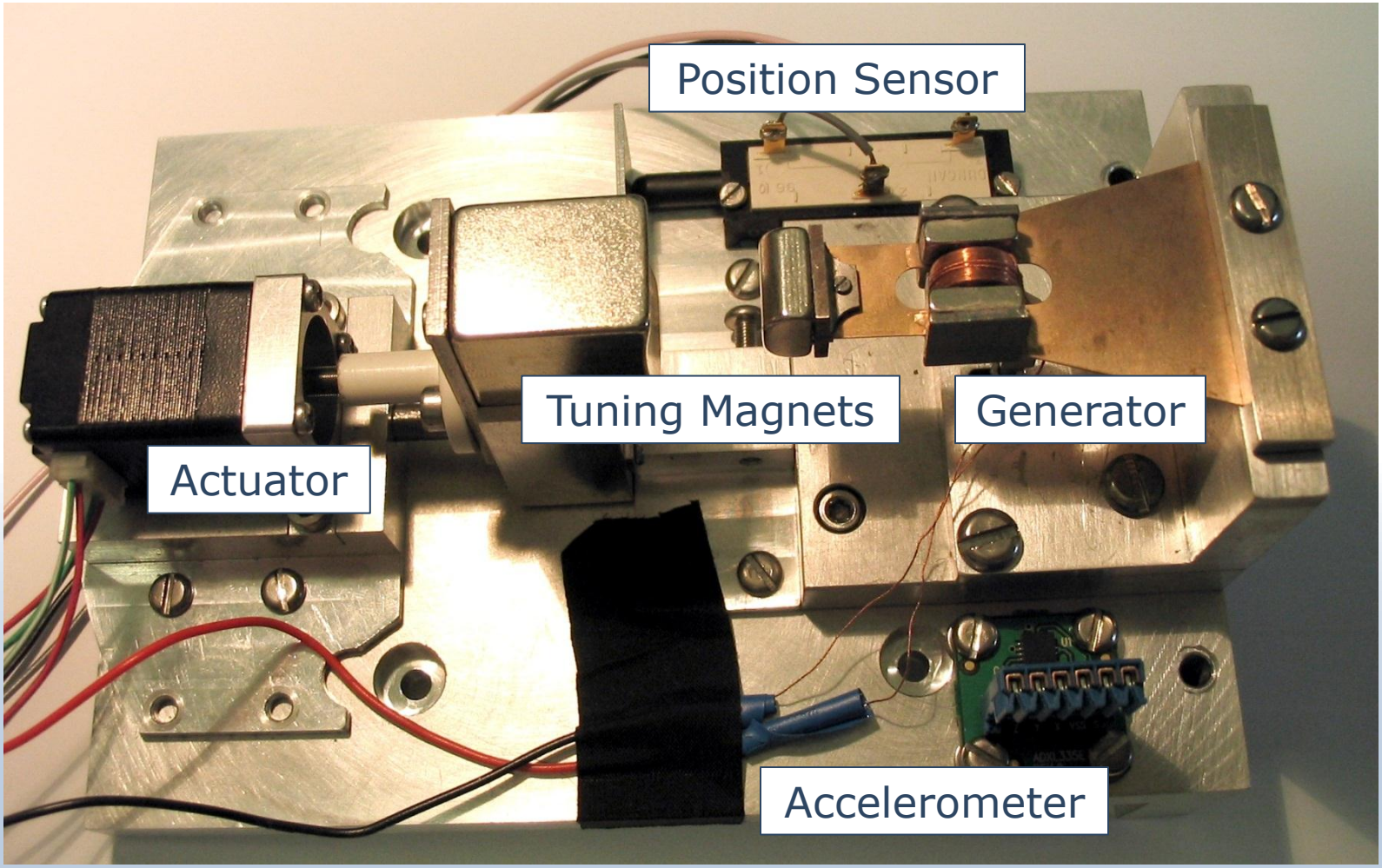
Tuneable Energy Harvester



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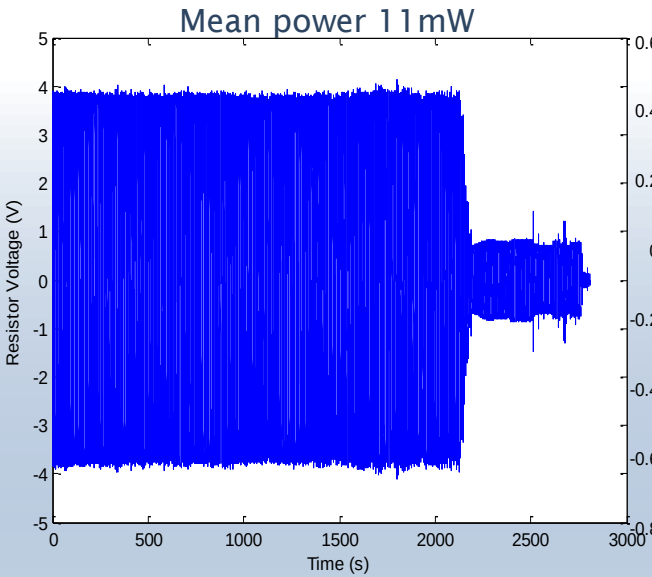
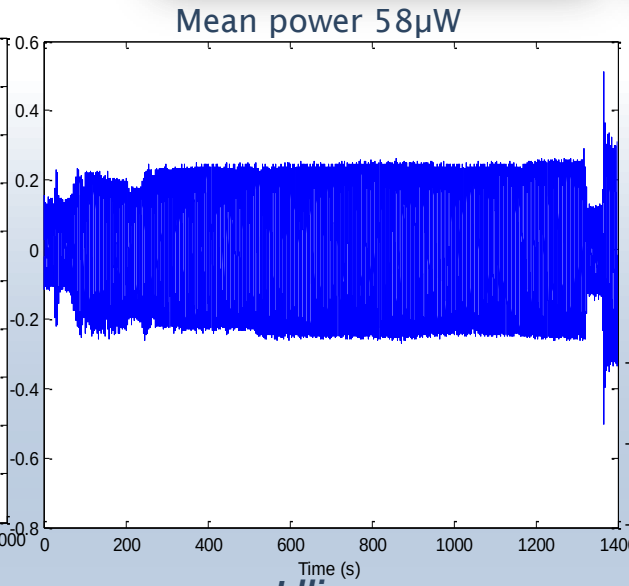
Results

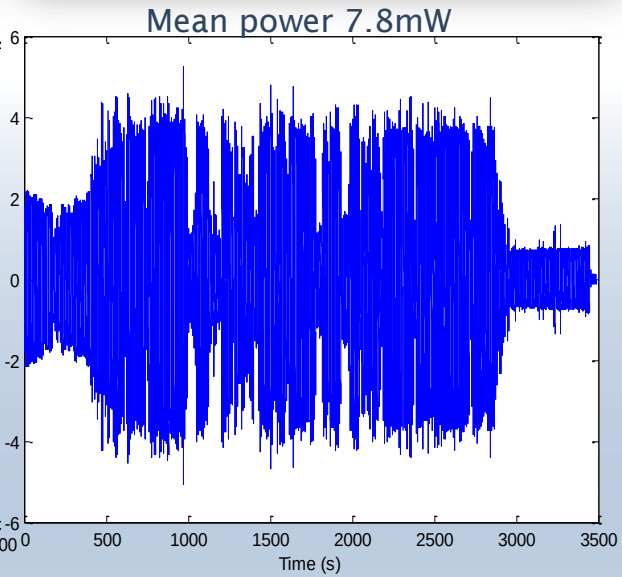
- Manually tuned
- 300Ω load



'Out' direction



Idling



'Return' direction

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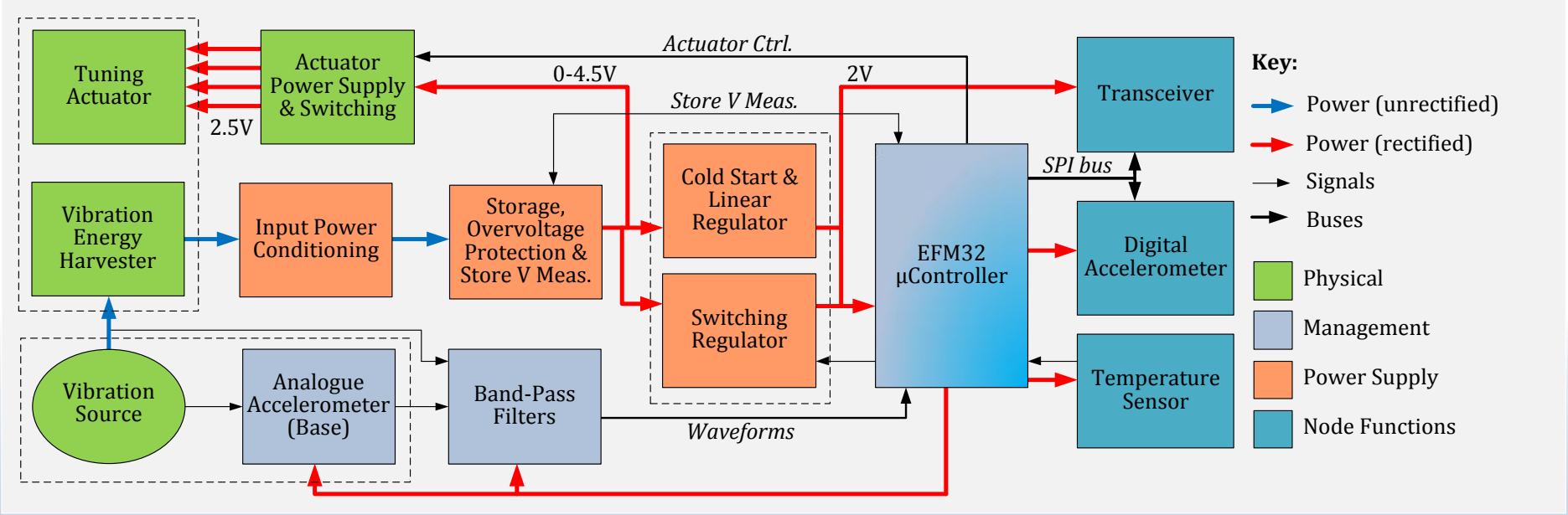
System Diagram



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Project Details

- £1.6M, three-year, EPSRC-funded project
- Kicked off in Q4 2009
- Over 25 people at four UK institutions:

University of Southampton
Newcastle University
Imperial College London
University of Bristol

- Industrial advisory board:

Diodes Incorporated
ARM
dialog Semiconductor
Mentor Graphics

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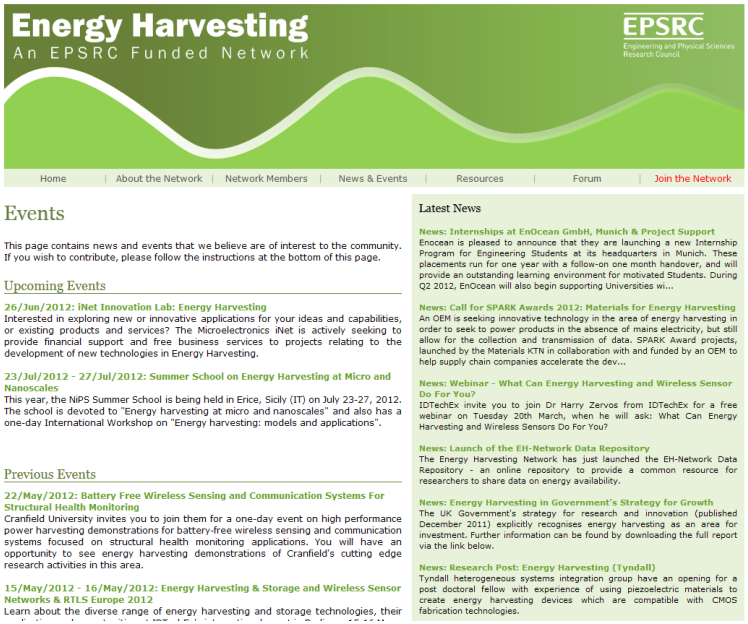
Project Partners

- University of Bristol
  - Input power conditioning: maximise harvester utilisation
- Newcastle University
  - Asynchronous circuits for power-modulated computing
- Imperial College
  - Novel tuning mechanisms (including MEMS)

The EH Network: *eh-network.org*

- **Started 01 March 2010, funded by EPSRC for 3 years**
  - Motivated by UK/Europe's strength in EH, potential for new applications and to identify new research challenges
  - Objectives: define research challenges, catalyse collaboration, disseminate advances
  - UK Steering Board (academic/industrial)
  - 304 members in 243 companies/institutions worldwide, ~50/50 academia/industry
- **EH Network Data Repository**
  - An open-access EH database for researchers to download and share data
  - Wide range of sources – cars, bridges, ferries, humans, CHP, machinery etc



Join for free: **http://eh-network.org/join.php**

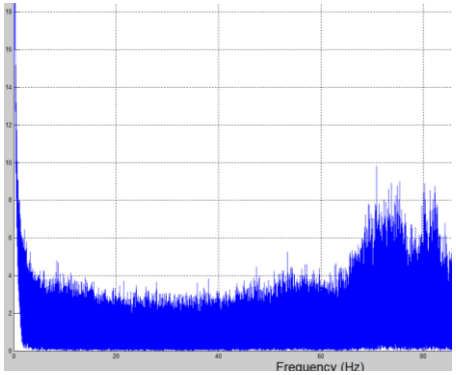
Energy Harvesting

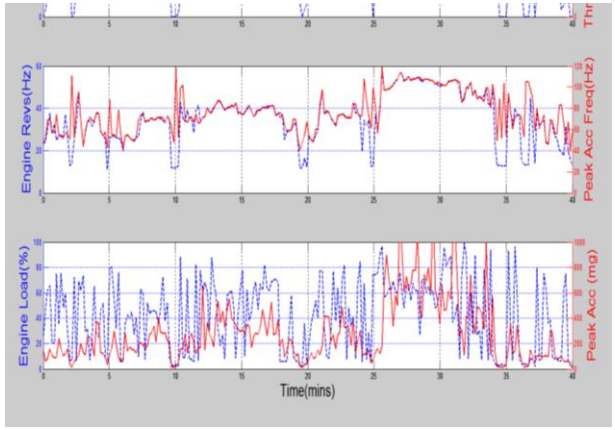
www.eh-network.org

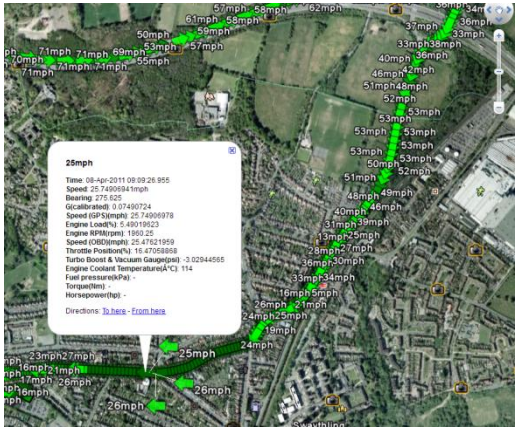
EPSRC

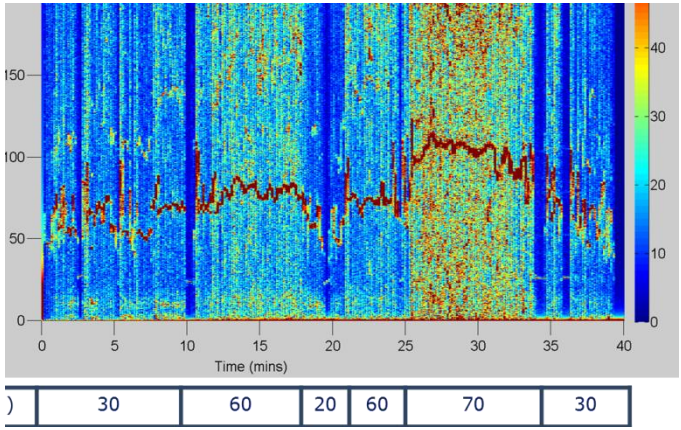
Engineering and Physical Sciences Research Council

EH Network Data Repository









Visit: **http://eh-network.org/data**

Join for free: **http://eh-network.org/join.php**

Energy Harvesting

www.eh-network.org

EPSRC
Engineering and Physical Sciences Research Council

EPSRC
Engineering and Physi
Research Council

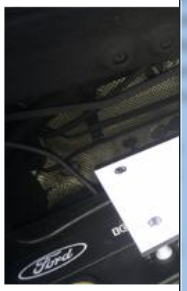
Ho

Vibration

General Inform

Contact: Dr Alex We
Institution: Universi
Parameter: Vibratio
Specific Location: F
Data Duration: 00d
Sampling Frequenc
Date Obtained: 08-

Acknowledgment:
Approach"



Detailed Test In

2011-11-08 Ford Focus Engine (Plate).csv [Read-Only] - Microsoft Excel

File | Home | Insert | Page Layout | Formulas | Data | Review | View

Clipboard | Font | Alignment | Number | Styles | Cells | Editing

D9 | Uint16

	A	B	C	D	E	F	G	H	I	J	K	L
1	Recording	21:11.4										
2	FromSam	0.0s										
3	ToSample	3879.8s										
4												
5	Channels	3										
6	PerChann	1024.066										
7												
8	ChannelN	ChannelN	Units	DataType	RangeMin	RangeMax	DataScale	DataOffse	SensorSca	SensorOffset		
9	Ain 1	1	Volts	Uint16	0	4095	0.004883	-10	1	0		
10	Ain 2	2	Volts	Uint16	0	4095	0.004883	-10	1	0		
11	Ain 3	3	Volts	Uint16	0	4095	0.004883	-10	1	0		
12												
13	Ain 1	Ain 2	Ain 3									
14	0	0	0									
15	0	0	0									
69283	0.136719	0.107422	-0.15625									
69284	-0.10254	-0.05371	-0.00488									
69285	-0.02441	0.004883	-0.11719									
69286	0.078125	-0.04395	0.014648									
69287	-0.25879	0.029297	-0.09766									
69288	0.078125	-0.04883	0.019531									
69289	-0.18066	-0.07813	-0.05859									
69290	-0.15137	0.009766	0.107422									

2011-11-08 Ford Focus Engine (P

Ready | 100%

Raw data in time domain available as .csv file.

Analysis

rameters
024 Hz
0 s
10 s
s

s performed: 3870

vibration axis: X

l: 1946.7 mg_{peak} at 35.0 Hz at 35 s

el Ampl above 50% of Max Ampl: 142.0 s (3.7 %)
q Range (above 50% of Max Ampl): 22.0 ... 234.0 Hz
eq (above 50% of Max Ampl): 63.7 Hz

eleration Ampl (whole test): 470.8 mg_{peak}
eleration Freq (whole test): 69.9 Hz

l: 1022.0 mg_{peak} at 35.0 Hz at 2918 s

el Ampl above 50% of Max Ampl: 322.0 s (8.3 %)
q Range (above 50% of Max Ampl): 78.0 ... 124.0 Hz
eq (above 50% of Max Ampl): 92.7 Hz

eleration Ampl (whole test): 250.5 mg_{peak}
eleration Freq (whole test): 54.6 Hz

l: 1490.7 mg_{peak} at 35.0 Hz at 3105 s

el Ampl above 50% of Max Ampl: 431.0 s (11.1 %)
q Range (above 50% of Max Ampl): 69.0 ... 124.0 Hz

Visit: **http://eh-network.org/data**

Join for free: **http://eh-network.org/join.php**

Events: Workshops and Conferences

- 3 workshops to define new challenges: human power, structural monitoring, and MEMS/NEMS
  - Road-mapping reports available to download from the Network's website
- Energy Harvesting 2011 (EH Network's annual conference) was held in February 2011 (London)
- Energy Harvesting 2012 was held in March 2012 (London)
  - ~100 attendees, 12 presentations (academia/industry), 10 PhD posters, 5 company stands
  - Will be held again next year – join to find out more!

Join for free: **http://eh-network.org/join.php**

holistic
energy harvesting

Thank you!

Any Questions?

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