Energy Harvesting Technologies for Structural Health Monitoring Applications

2013 IEEE Conference on Technologies for Sustainability (Sustech)

DoubleTree by Hilton Portland
Portland, Oregon, USA

01 Aug – 02 Aug, 2013

Changki Mo and Joseph Davidson

Dynamics and Controls Laboratory

School of Mechanical and Materials Engineering

Washington State University Tri-Cities, Richland, WA

WASHINGTON STATE UNIVERSITY
TRI-CITIES
World Class. Face to Face.

Outline

- Introduction to Energy Harvesting
- Motivation of Energy Harvesting for Structural Health Monitoring
- Case Studies of Energy Harvesting Technologies Applied to Structural Health Monitoring
  - Sources of Ambient Energy - Mechanical vibrations, Wind, Kinetic Energy of Rotation, Thermal Energy, and Solar Energy
  - Frequency Tuning
- Conclusion and Discussion

• Energy Harvesting

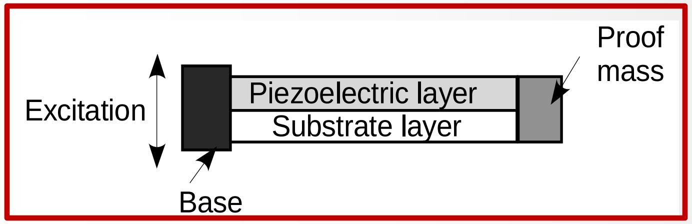
➢ To capture energy readily available from external sources and to convert into usable electrical energy

➢ Small, wireless autonomous devices, like those used in wearable electronics and wireless sensor networks

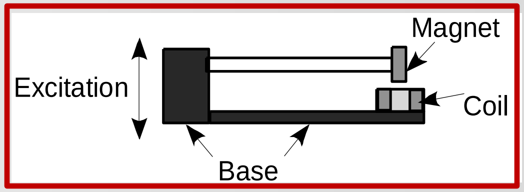
➢ **Typical external sources for useful energy**

➢ Vibration, linear/rotational motion, light, pressure, wind, solar, temperature change, etc.

➢ Much of the research and commercialized devices are vibration-based energy harvesters.



Unimorph piezoelectric energy harvester



Electromagnetic energy harvester

➢ Some vibration sources available around us

Table 1. Summary of several vibration sources.

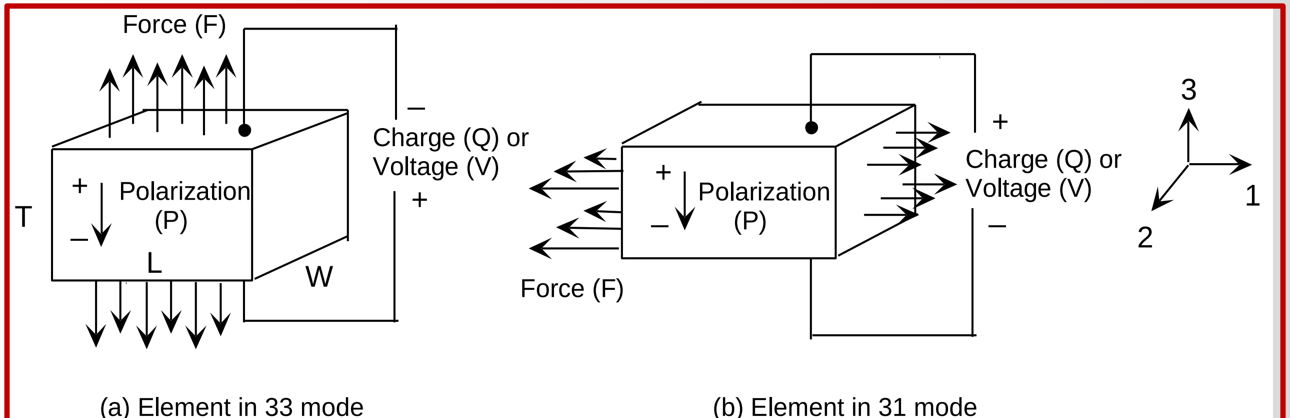
Vibration source	Peak acceleration (m/s^2)	Frequency (Hz)
Base of 3-axis machine tool	10	70
Kitchen blender casing	6.4	121
Clothes dryer	3.5	121
Door frame just as door closes	3	125
Small microwave oven	2.25	121
HVAC vents in office building	0.2–1.5	60
Wooden deck with foot traffic	1.3	385
Breadmaker	1.03	121
External windows (2 ft × 3 ft) next to a busy street	0.7	100
Notebook computer while CD is being read	0.6	75
Washing machine	0.5	109
Second story floor of a wood frame office building	0.2	100
Refrigerator	0.1	240

(Roundy, 2005, JIMSS)

• Overview of piezoelectric energy conversion

➢ Piezoelectric materials have the ability **to generate an electrical charge when deformed by an applied mechanical load** or inversely to exhibit strain under the influence of an applied electrical field.

➢ The relationship between mechanical input and electrical response depends on **the piezoelectric properties of the material, the size and shape of the element**, and **the direction of mechanical excitation** and **electrical response**.



(d_{33} mode) **(d_{31} mode)**

Schematic of force/charge relationship on piezoelectric generator elements

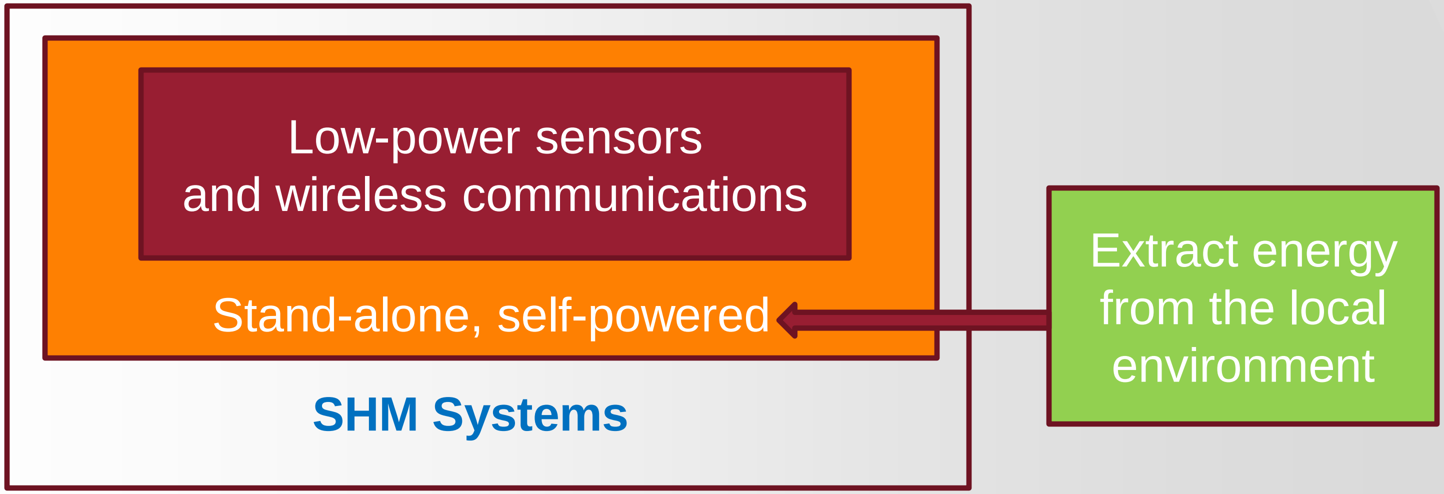
➢ Available electrical power output of the element

$$Power = \frac{1}{2}VQf = \frac{1}{2}\sigma^2 g_{ij} d_{ij} TWLf$$

Where, σ is induced stress, g_{ij}, d_{ij} piezoelectric coefficients, and f is frequency.

• Motivation of Energy Harvesting for Structural Health Monitoring (SHM)

- SHM is the process of damage detection in machinery, aerospace, and civil structures.
- The need for autonomous monitoring of machinery and structures has been ever-increasing.
- Autonomous SHM systems typically include **embedded sensors**, **data acquisition**, **wireless communication**, and **energy harvesting systems**.



- Ambient energy sources could be vibrations, thermal gradient, sunlight, wind, pressure, kinetic energy of rotation, etc.

- **Harvesting energy using piezoelectric materials** by converting applied stress to electricity is most common.
- In SHM application, the piezoelectric material would be stressed due to vibrations or direct loading in a structure.
- Other methods to harvest energy such as electromagnetic, magnetostrictive, or thermoelectric generator as well as sunlight and wind are reviewed.
- Developments in energy harvesting technologies for SHM sensor systems prior to 2007 were reviewed by Park et al. (Los Alamos National Lab, 2008). Systems design considerations, sensor modalities, network strategies, and dynamic power requirements of SHM sensor systems were considered.
- **Concise introductory survey of recent developments (from 2008 to 2013)** in the methods of energy harvesting for the powering of wireless SHM systems, in particular related to machinery, civil, and aerospace applications.

WASHINGTON STATE UNIVERSITY TRI-CITIES
World Class. Face to Face.

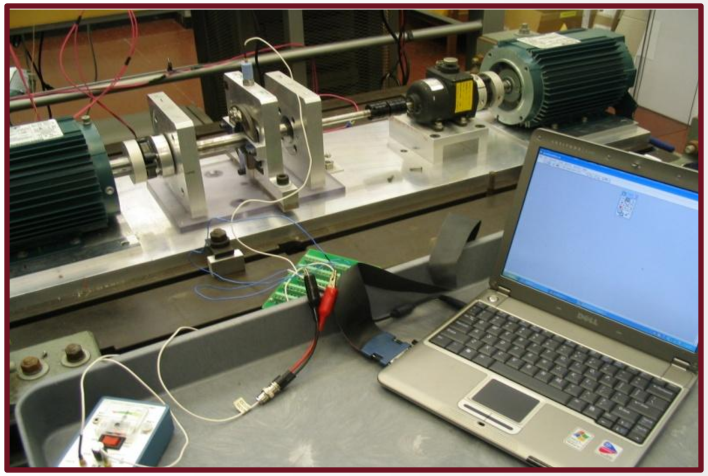
- **Sources of Ambient Energy**

➢ **Mechanical Vibrations**: Typically, the electrical energy is generated by applying strain energy from the vibrations to a piezoelectric material, which become electrically polarized when subjected to strain, or to displace an electromagnetic coil.

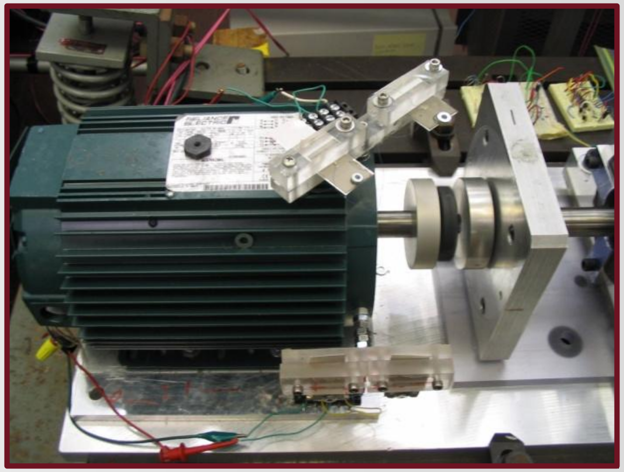
◆ **Wireless Self-Powered Machinery Diagnosis System**

by Clark, Romeiko, Charnegie, Kusic, and Mo (2007)

➡ Wireless measurement system for use in diagnosis of the state of a rotating **machinery system**

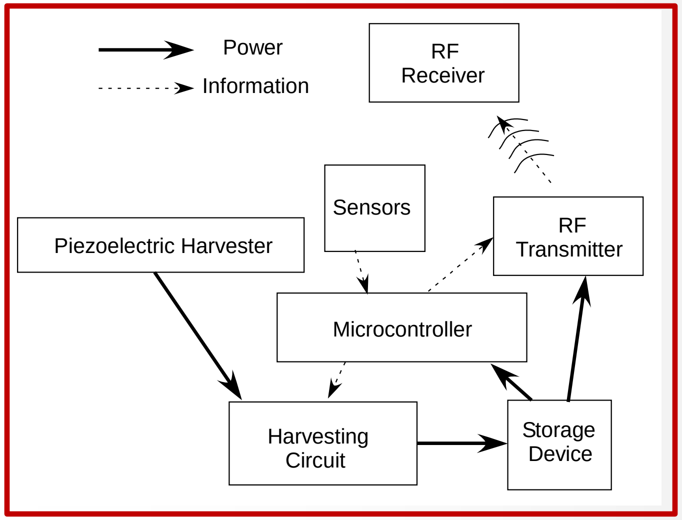


Motor test rig used as vibration source

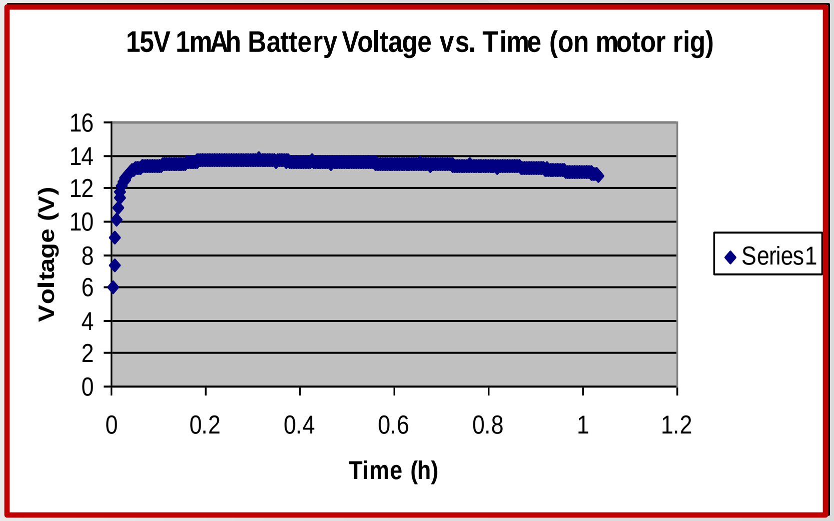


Close-up of the motor
with the beam harvesters attached

- Monitor the health of machinery and structures without any power source that requires manual maintenance or replenishment by using a system that converts vibration energy into electricity using piezoelectric materials.

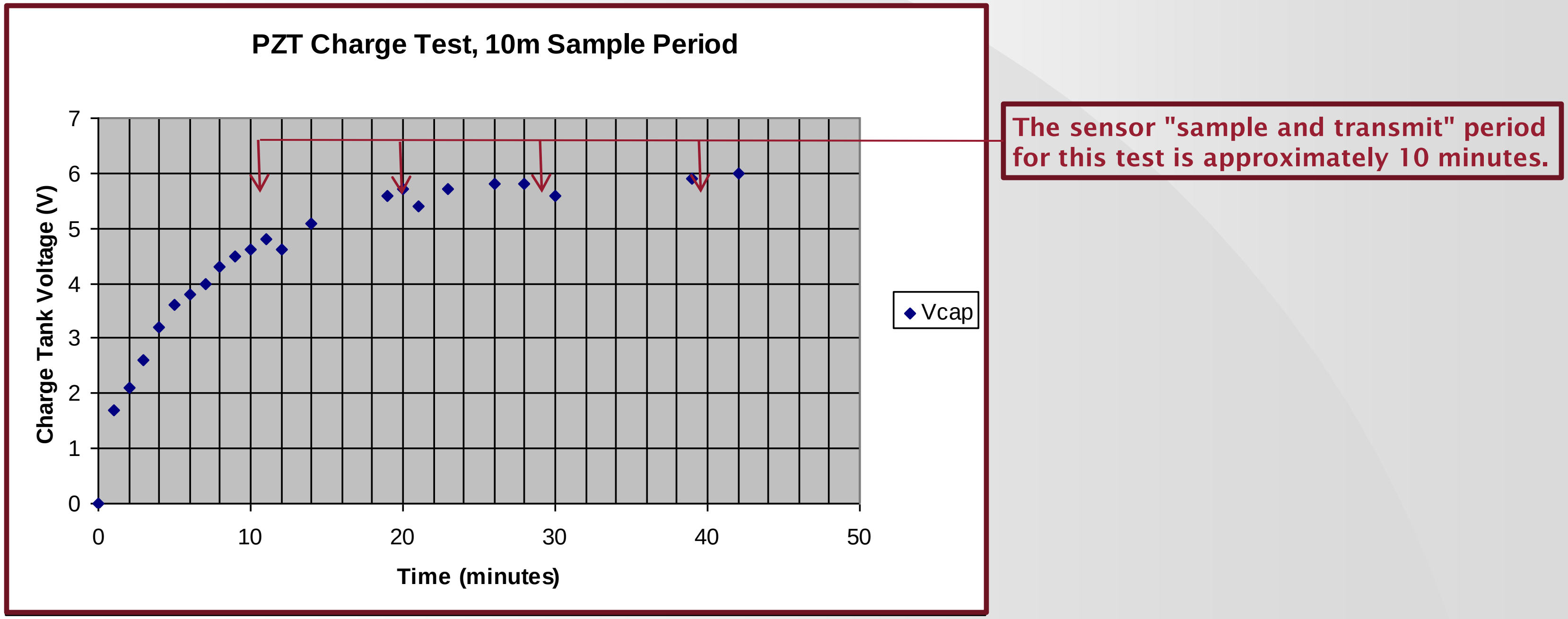


Schematic of microcontroller-based harvesting, data acquisition, and communications circuit, and accompanying battery



Battery-charging results for dual bimorph beams

- Test results show that generated current is 0.38-0.4mA RMS.
  The voltage is 30V peak-to-peak, resulting in approximately 15V rectified power to be supplied to the battery.
  Average power generation is just over 1 mW.



Time history of capacitor voltage (3300μF) **as it is charged by the piezoelectric harvester and momentarily discharged by microcontroller circuit .**

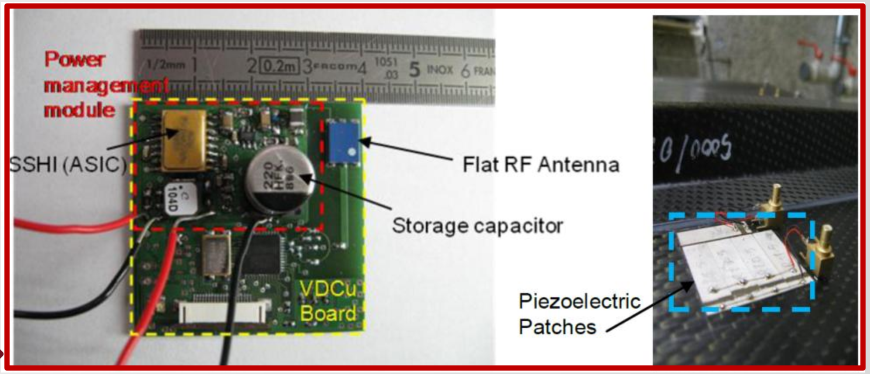
- By mounting the beams on the motor, energy could be harvested and stored in a battery or capacitor.
- It was shown that the rate of harvested energy was sufficient to power a microprocessor and accompanying wireless communications hardware to enable two sensors to be read (through the A/D converter on the microcontroller) and their data transmitted to a receiver once every ten minutes.

WASHINGTON STATE UNIVERSITY TRI-CITIES
World Class. Face to Face.

- **Energy Harvesting Wireless Sensor for Rotating Helicopter Components** by Arms et al. (2008)

Concept for wireless energy harvesting systems for helicopter flight test and in service structural loads tracking.

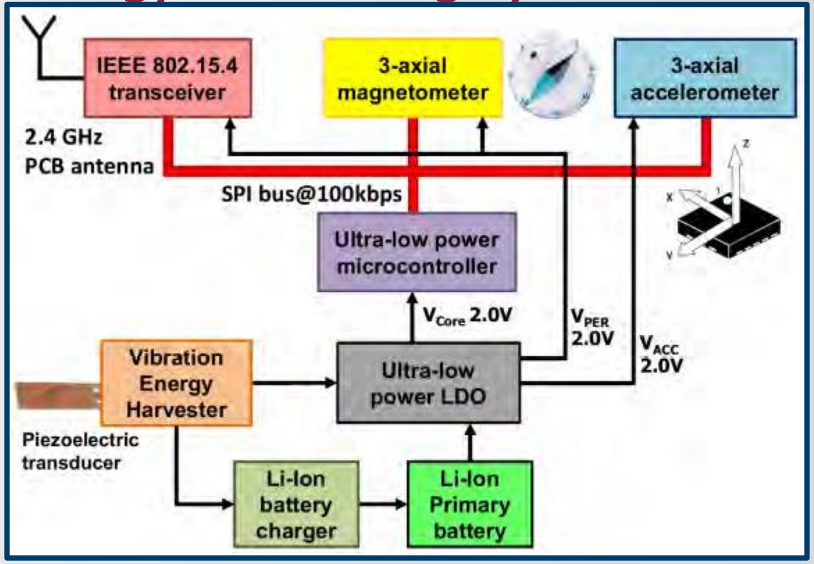
MicroStrain's energy harvesting, wireless loads tracking pitch link installed on Bell M412 .



VDCu Electronics and piezoelectric patches installed on the structure

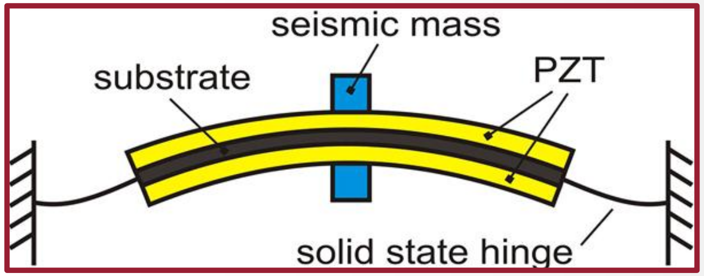
- **Smart Wireless Network of Piezoelectric Patches for Damage Detection in Airplane and Helicopter** by Dumas, Lani, Monnier, Smaili, and Loyer (2011): 0.2 mW

- **Wireless Sensor Device with Vibrational Energy Harvesting System for Safety of Machinery with Trailer**
  by Dondi, Napoletano, Bertacchini, Larcher, and Pavan (2012): 0.85mW

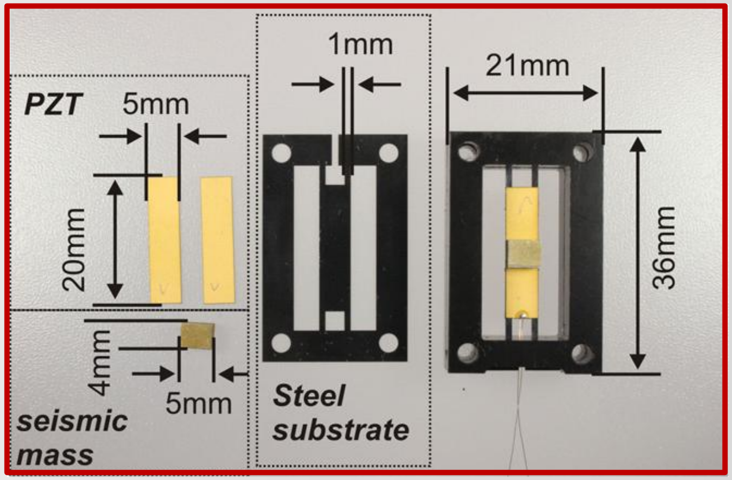


Architecture of the WED device of the wireless sensor system for autonomous vehicle motion tracking.

- **Wireless Sensor Nodes Powered by the Harvester from the Railway Sleeper in a Tunnel**
  by Wischke, Masur, Kröner, and Woias (2011): 0.4mW



Schematic design of the vibration harvester



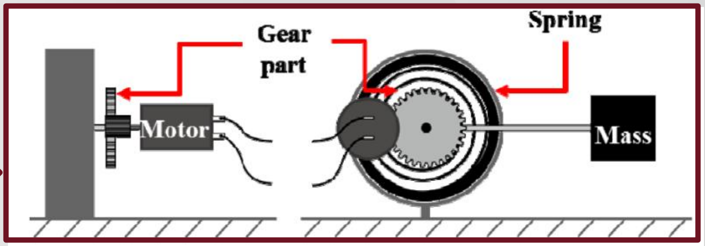
Harvester components and the assembled.

- **Analysis Combining Civil Infrastructure Systems and Energy Harvesting with Piezoelectric Materials**
  by Erturk (2011)

Examine the Feasibility of using the Low Frequency Vibrations to Power SHM Sensors

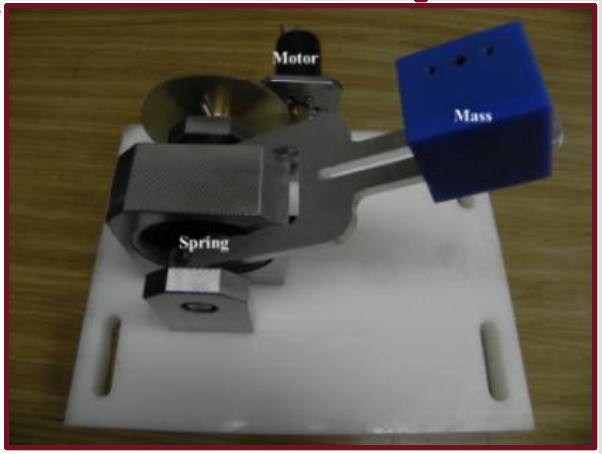
- **A Field Test on an In-service Cable-stayed Bridge using an Electromagnetic Energy Harvester**
  by Jung, Kim, and Park (2012)

: 0.17mW from deck, 15.46mW from stay cable



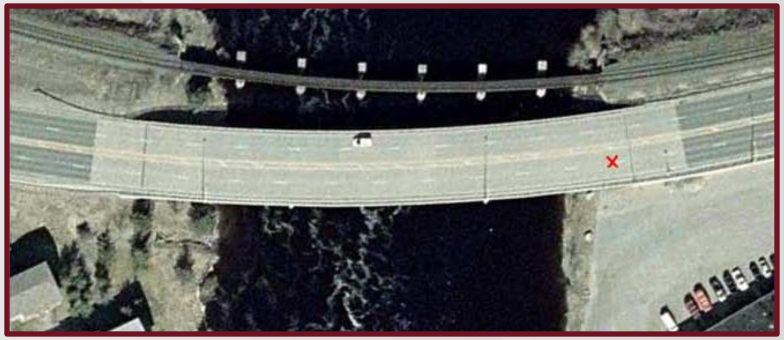
Schematic of the tested electromagnetic generator

Installed energy harvester



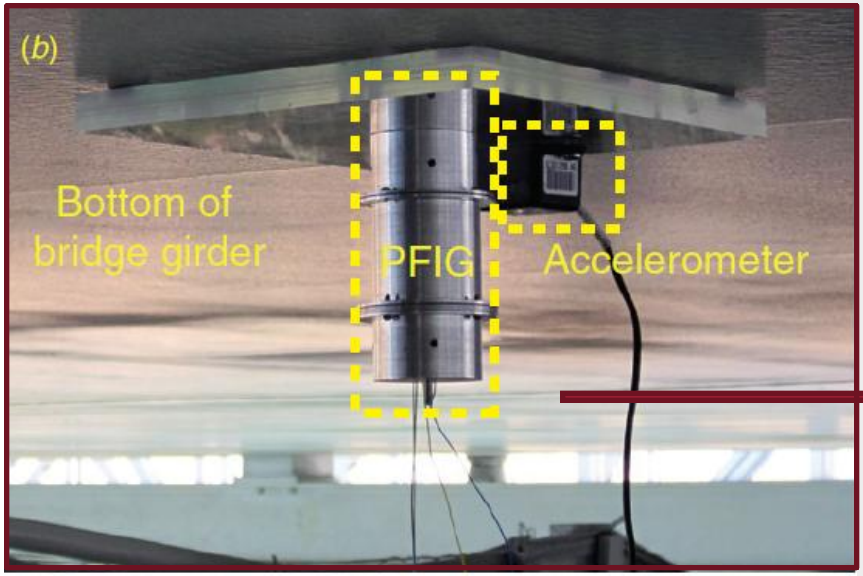
Prototype device

- **Another Field Test using Electromagnetic Energy Harvester on a Highway Bridge**
  by Sazonov, Li Curry, and Pillay (2009)
: 12.5mW, 10mm displacement at 3.1 Hz



Sensor location for the field test of the self-powered bridge sensor

- **Parametric Frequency-increased Generator (PFIG) for Low Acceleration, Low Frequency, and Non-periodic Vibration**
  by Galchev, McCullagh, Peterson, and Najafi (2011): 57μW, $0.54 m/s^2$, 2Hz



The harvester attached underneath the bridge girder alongside a Crossbow accelerometer

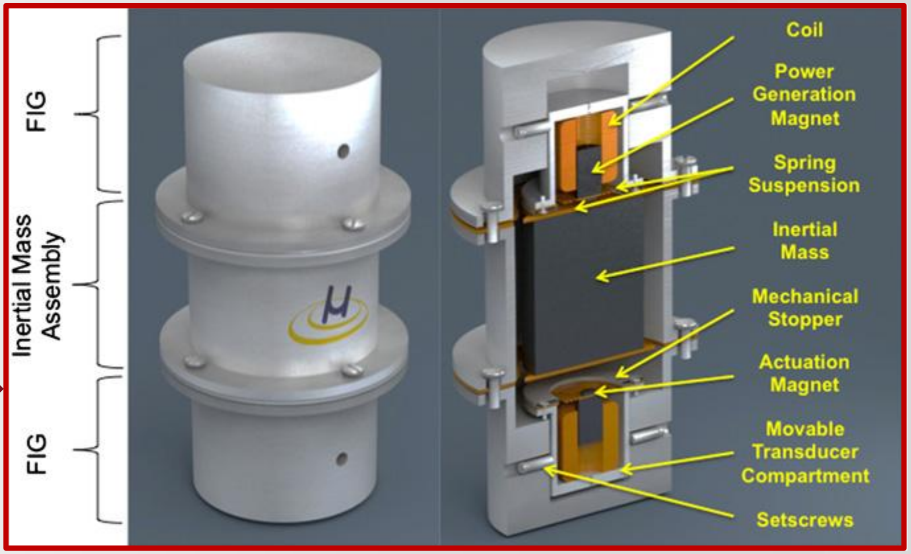
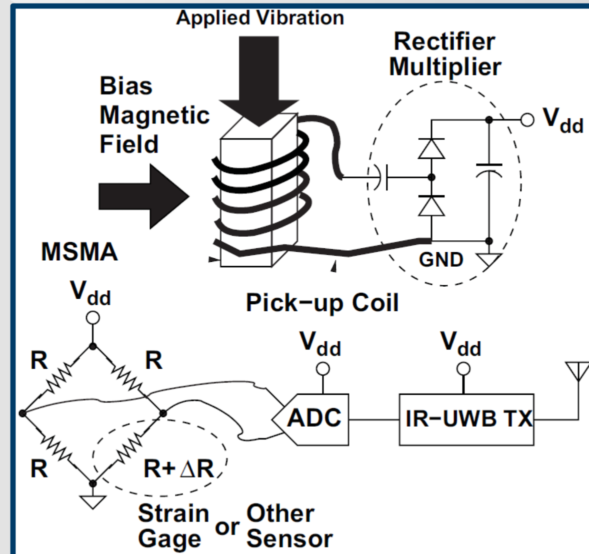


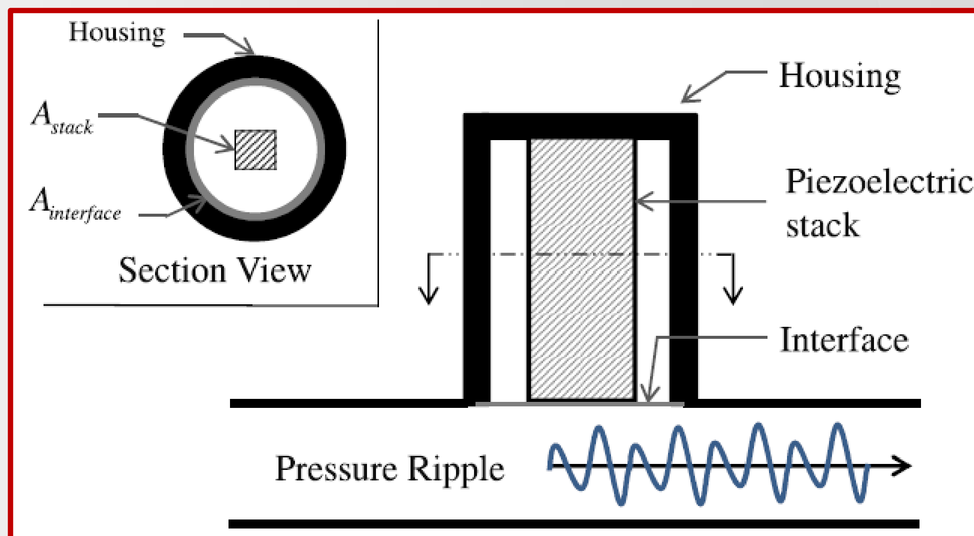
Illustration of the bridge PFIG harvester implementation

- **Magnetic Shape Memory Alloy (MSMA) for Monitoring of Bridges**
  by Wardlaw, Karaman, and Karsilayan (2013)
  : 0.1mW



Schematic of the self-powered wireless sensor using MSMA

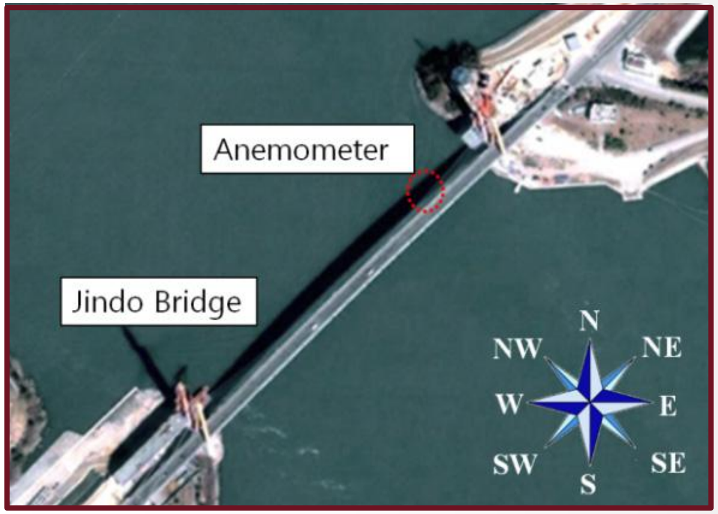
- **Hydraulic Pressure Energy Harvesters (HPEH)**
  in Hydraulic Systems
  by Cunefare et al. (2013)
  :1.2mW



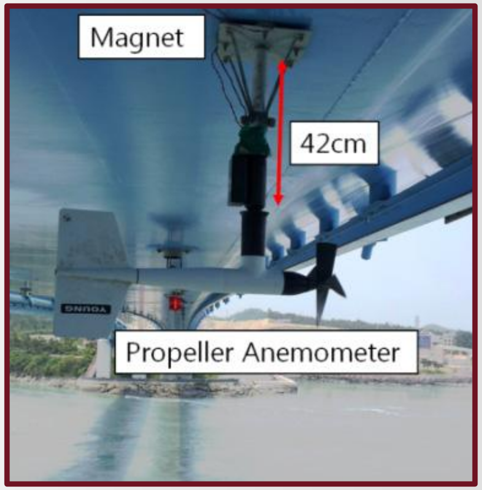
Hydraulic pressure energy harvester schematic

➢ **Wind**: Given that many bridges are located in windy areas, wind power generation has received much attention as a potential power source for wireless SHM sensors

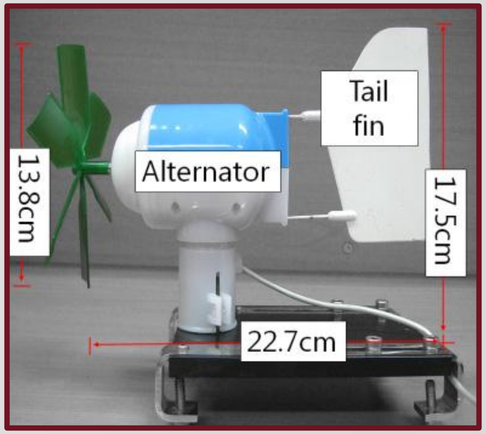
◆ **Micro-wind Turbines to Power Wireless Sensors on a Cable-stayed Bridges**
by Park, Jung, Jo, and Spencer (2012): 439mW @7m/s



Wind record measured at the Jindo Bridge



anemometer at the bottom of the girder



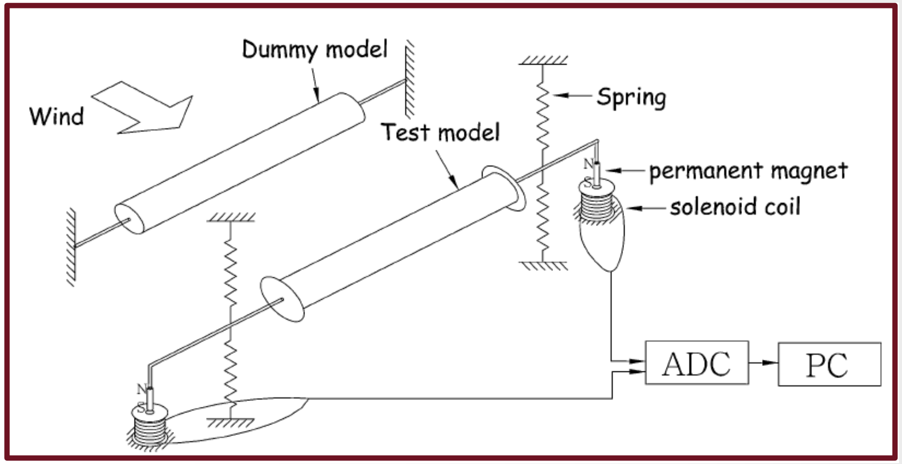
Horizontal-axis wind turbine

WASHINGTON STATE UNIVERSITY TRI-CITIES

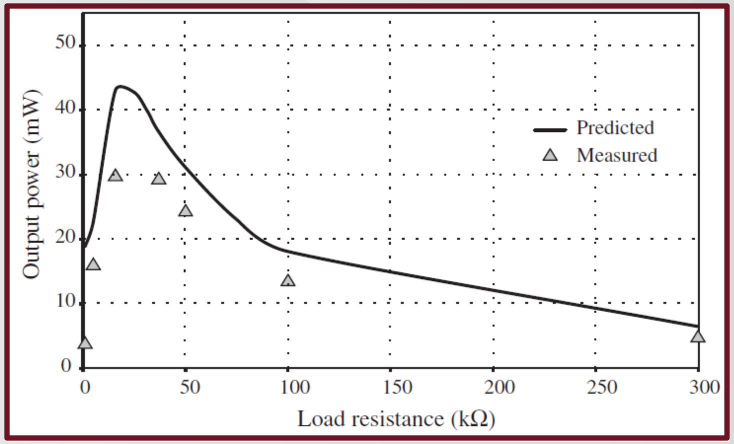
World Class. Face to Face.

Harvesting Energy from Aerodynamic Instability Phenomena such as Galloping, Flutter, and Vortex Induced Vibration

- **Electromagnetic Generator by Wake Galloping** by Jung, Lee, and Jang (2009)



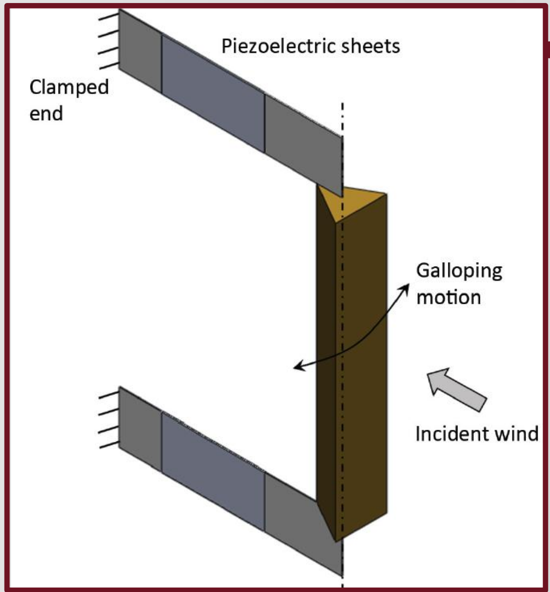
Schematic of experimental setup



Output power for an incident wind speed (10 mph)

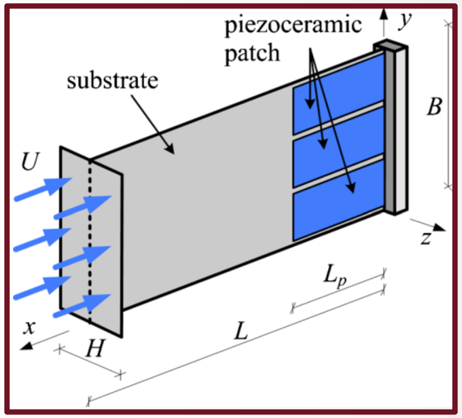
:0.3-1.13W @1.8-5.6m/s wind

- **Piezoelectric Wind Energy Harvester with Aerodynamic Galloping** by Sirohi and Mahadik (2011)
  :50mW @11.6 mph wind

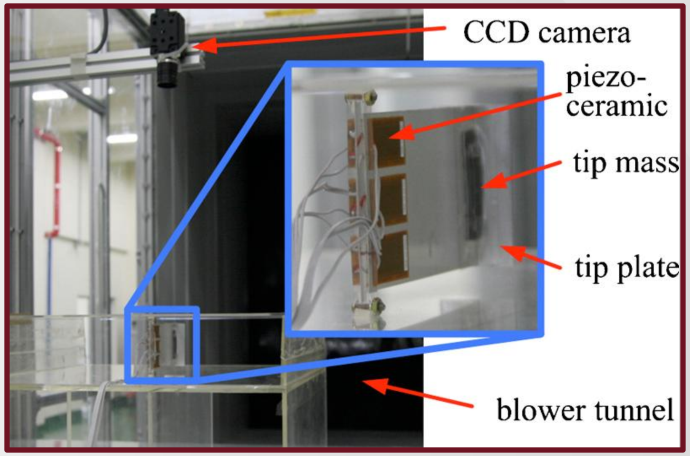


Galloping energy harvester with tip body having equilateral triangle cross section

- **T-shaped Piezoelectric Energy Harvester from Aeroelastic Flutter** by Kwon (2010): 4mW @4m/s wind



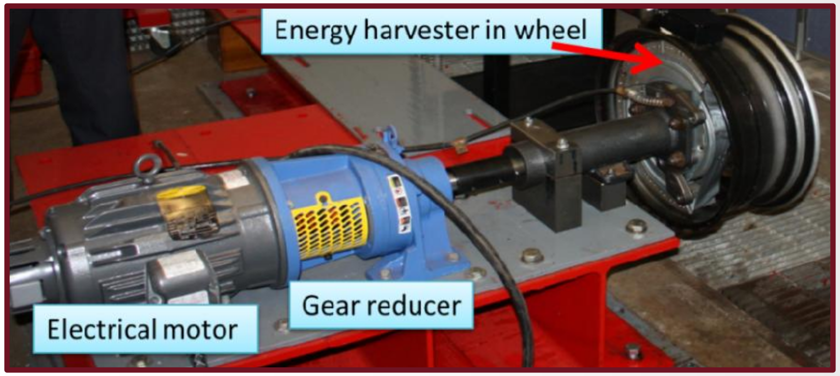
Schematic of the T-shaped Piezoelectric cantilever under fluid flow



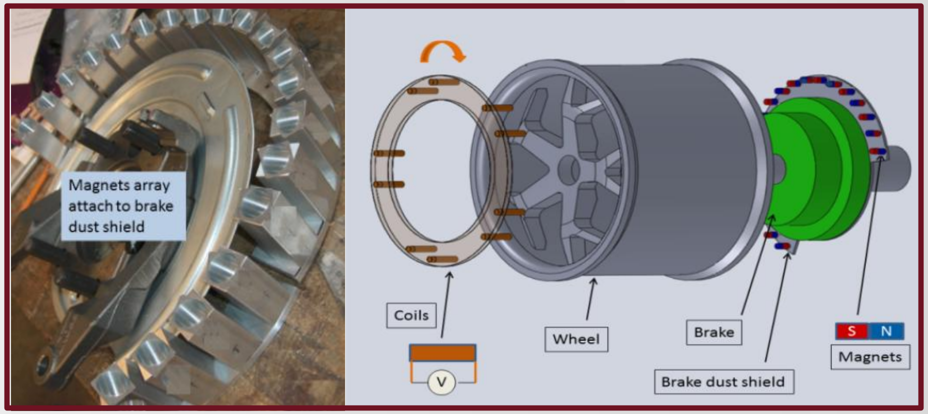
Experimental set-up of the harvester in the wind tunnel

- **Kinetic Energy of Rotation:** For all rotating machines and structures, like turbines, for example, real-time condition monitoring is highly desirable to achieve improved safety and equipment performance.

- **Rotating Energy Harvester for Powering a Real Time Tire Pressure Monitoring System (TPMS)**
  by Wang Q., Zhang, Sun, McDaniel, and Wang M. (2012): $5W/cm^3$ @60mph

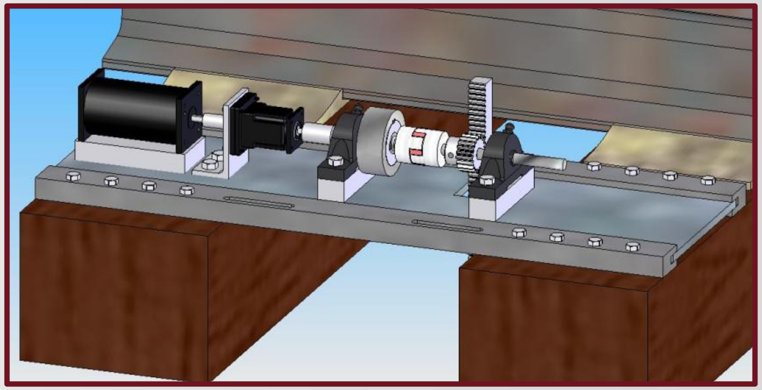


Experimental setup for the energy harvester prototype



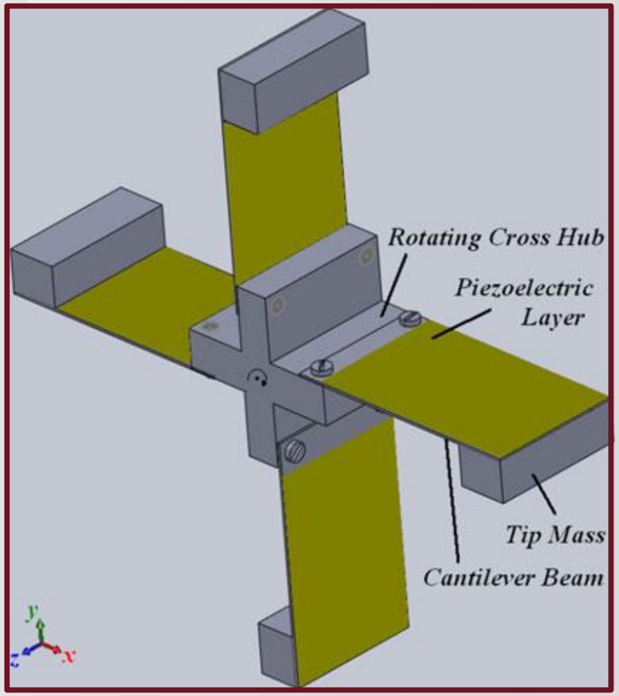
Mechanism of energy harvester

- **Harvesting Energy from Passing Railcars to Power Warning Lights and Track Health Monitoring Systems**
  by Nelson, Platt, Hansen, and Fateh (2009) :0.22W@11.5mph



Device shown mounted across two ties of a section of railroad track

- **Vibration-based Energy Harvester for Rotary Motion Health Applications**
  by Khameneifar, Arzanpour, and Moallem (2013)
: 6.4mW @138 rad/s shaft speed



Schematic view of the energy harvester mounted on a rotating hub

- **Electromagnetic Generator using Rotational Motion of Wind Turbine to Monitor Blades**
  by Joyce (2011): 41.1mW at 19rpm

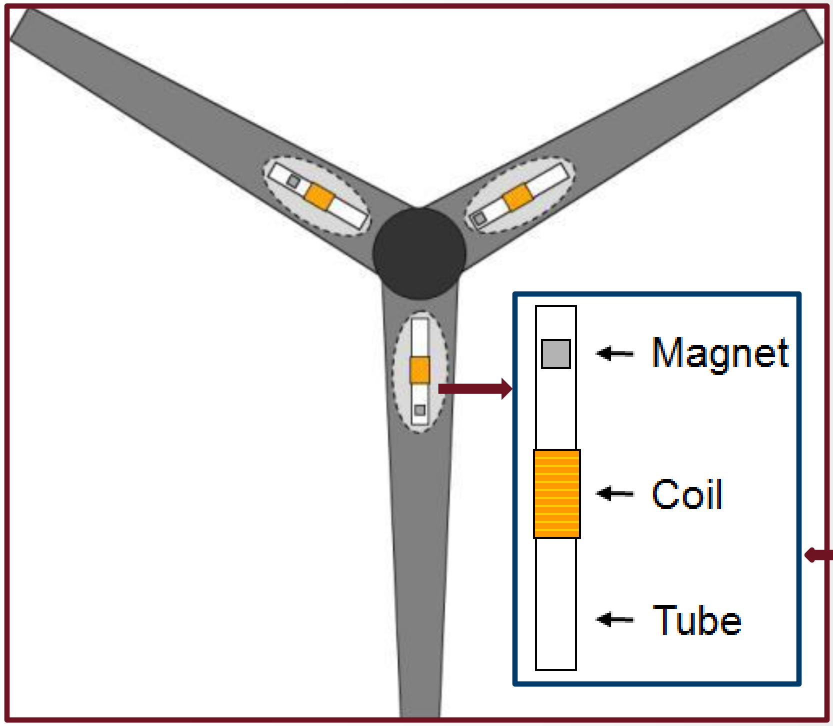
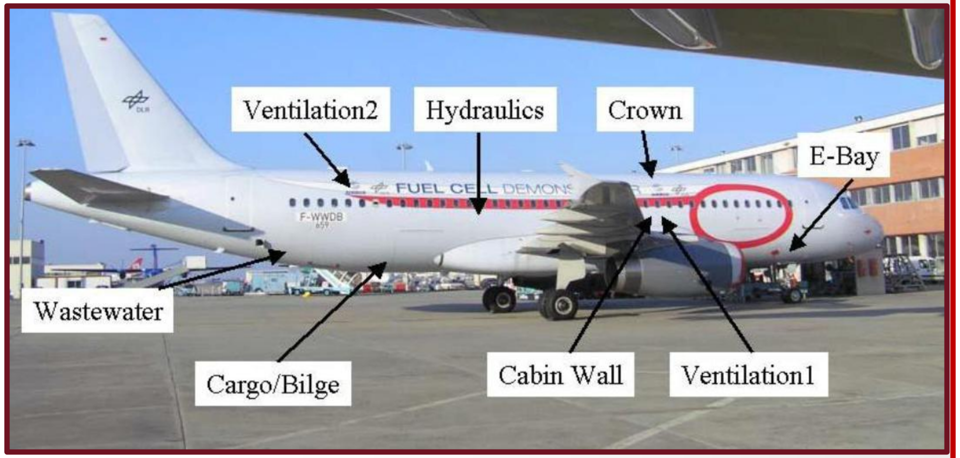


Diagram of the energy harvester assembly

Energy harvesters placed inside the blades of a wind turbine

- **Thermal Energy:** Use thermoelectric generators (TEGs). An advantage of a TEG compared to a vibration-based energy harvester is that it has no moving parts. A disadvantage is that TEGs are relatively inefficient when low thermal gradients are present.

- **TEG Power Output Simulation for Aerospace Application of Large Thermal Gradients**
  by Pearson, Eaton, Pullin, Featherston, and Holford (2012)



Locations of thermocouples used for the TEG power output simulation

	Peak Temperature Differential, ^{0}C	Peak Power, mW	Average Power, mW
Cargo skin Cargo Primary Insulation	40	34.15	22.58
Hydraulic Pipeline 1 Hydraulic Pipeline 2	20	7.97	3.07
Waste water tank Waste water ambient	15	5.46	2.99
E-bay fuselage skin E-bay primary insulation	35	18.72	6.42
Cabin wall fuselage skin Cabin wall primary insulation	30	13.36	3.97
Cabin wall fuselage skin Cabin wall secondary insulation	40	30.06	11.70

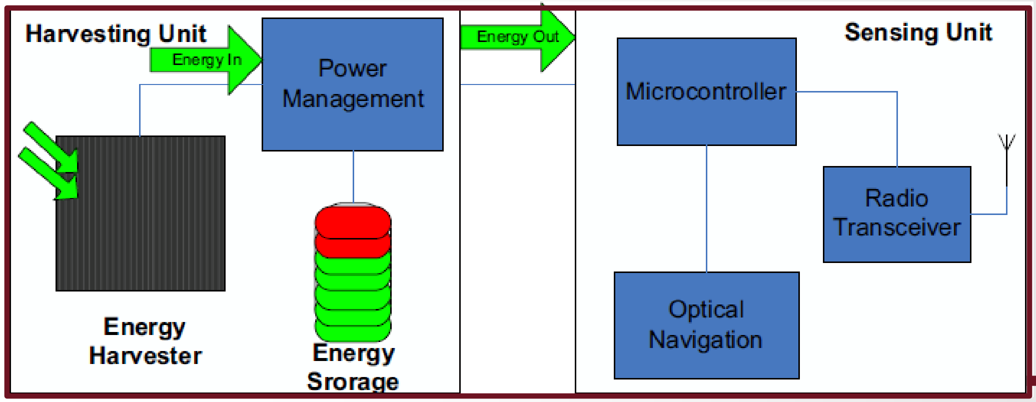
Simulated power levels for temperature gradients on an aircraft

- **Solar Energy:** Solar energy harvesters have also been applied to wireless sensing nodes for SHM.

- **Solar Energy Harvesters for Civil Structural Monitoring Applications** by Arms et al. (2008)

- **Solar Energy Harvesting Evaluation Kit for Crack Monitoring for Concrete Structures** by Hassan, Man, Ng, Bermak, and Chang (2012): Cymbet kit, 0.35mW@1000Lux

Solar powered wireless G-Link ® seismic sensors on Corinth Bridge, Greece



System architecture for crack monitoring sensor

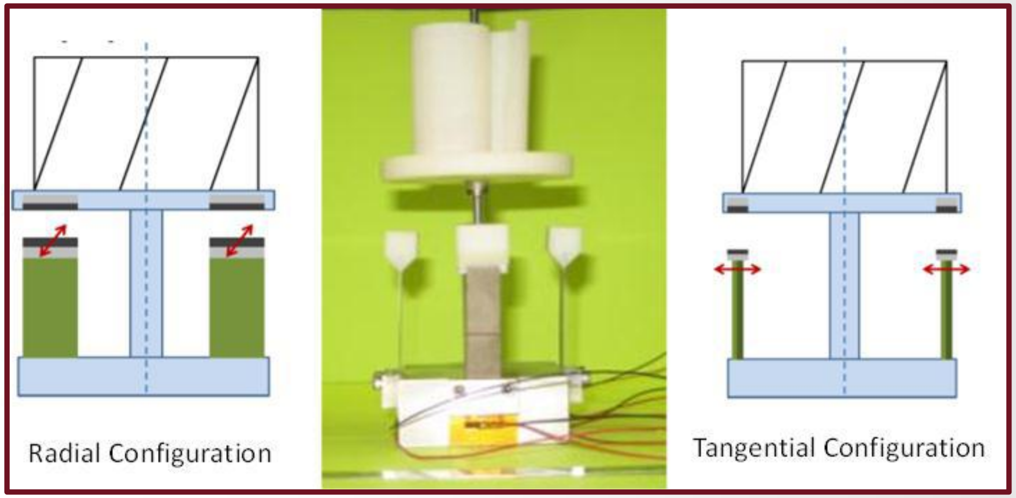
Hardware components used in crack monitoring

- **Multiple Energy Sources:** In many environments where multiple sources of ambient energy are present it may be possible to develop an energy harvesting strategy that utilizes multiple transduction mechanism.

- **Piezoelectric and Thermoelectric Harvesters for Bridge Health Monitoring** by Farinholt et al. (2010): requires15min to charge

- **Windmill and Piezoelectric Energy Generator to Power Wireless Sensor Node** by Godinez-Azcuaga et al. (2012)

:100 to 700mW @6-11mph wind



Vertical contactless nonlinear piezoelectric wind energy harvester

:10mW at 5mph wind

Windmills deployed on the pier

- **Frequency Tuning**

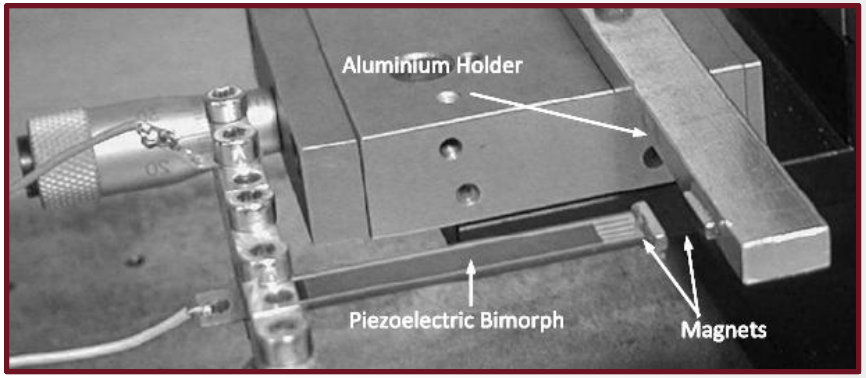
  Frequency matching can be difficult because of manufacturing tolerances, excitation frequency changes, and electric load changes.

- **Piezoelectric Buckled Beams for Random Vibration Energy Harvesting** by Cottone, Gammaitoni, Vocca, Ferrari, M., and Ferrari, V. (2012)

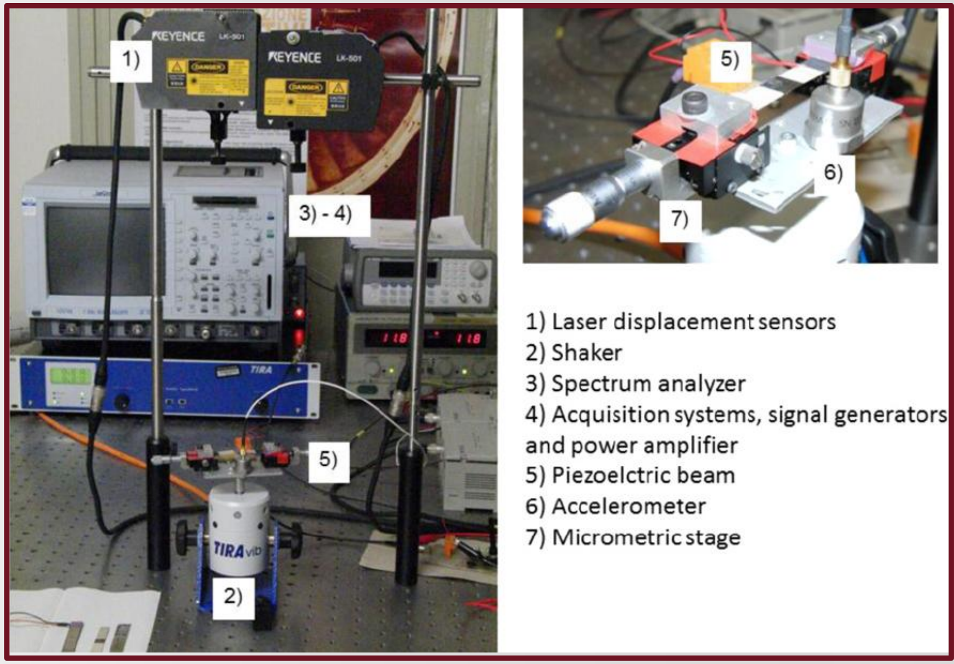
: 13 times higher @2g acceleration

- **Frequency Tuning for Piezoelectric Bimorph Beams by Magnets** by Al-Ashtari, Hunstig, Hemsel, Sextro (2012)

:increase 70% natural frequency



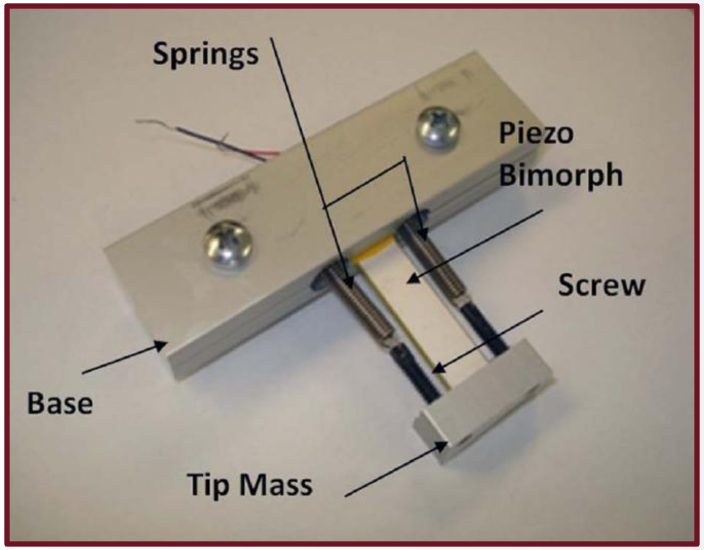
Experimental setup for frequency tuning by magnets



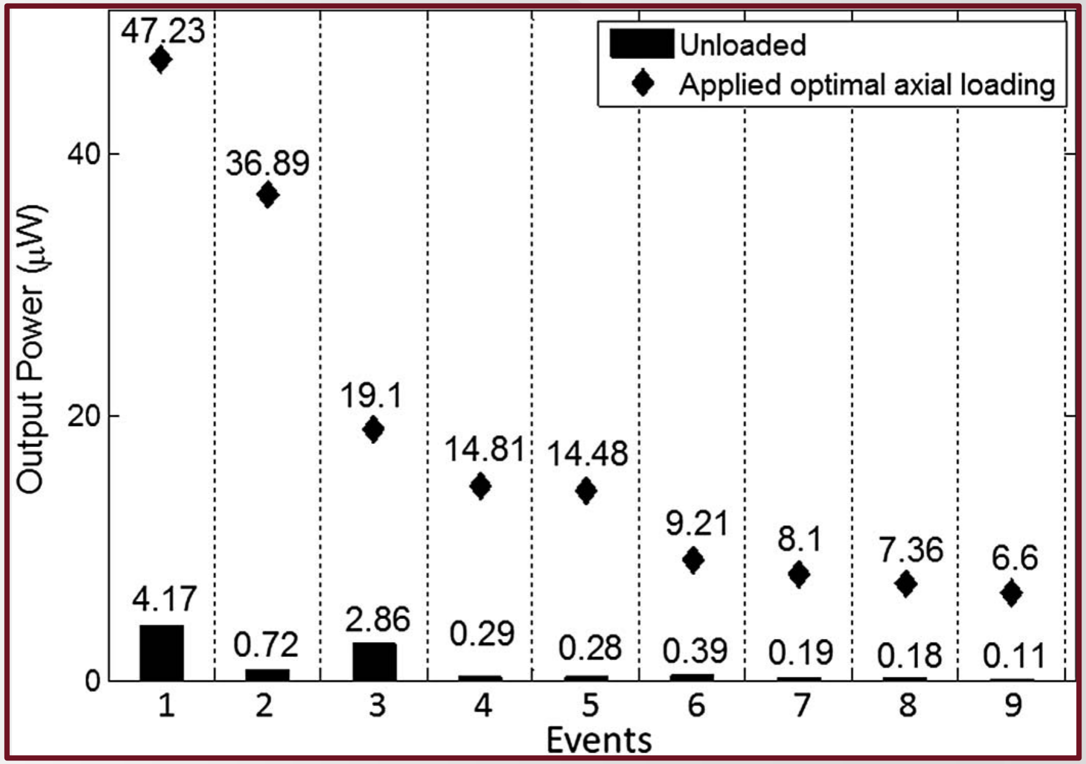
Experimental set-up for system testing

Tunable Vibration-based Energy Harvesting in Civil Structures

by Rhimi and Lajnef (2012)



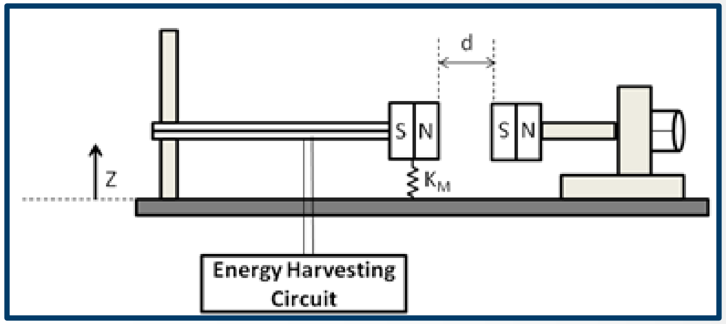
Test setup, loaded piezoelectric bimorph beam with attached tip mass



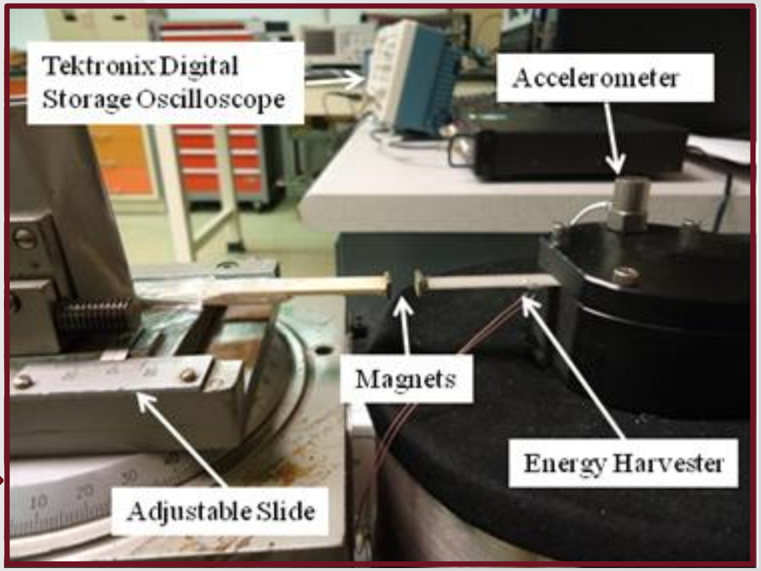
Average power output generated by a piezoelectric harvester subject to a set of example earthquake acceleration events for both the unloaded configuration and the configuration <u>with applied optimal axial loading</u>

Frequency Tuning for Piezoelectric Energy Harvester for Monitoring a Nuclear Facility's Ventilation Fan

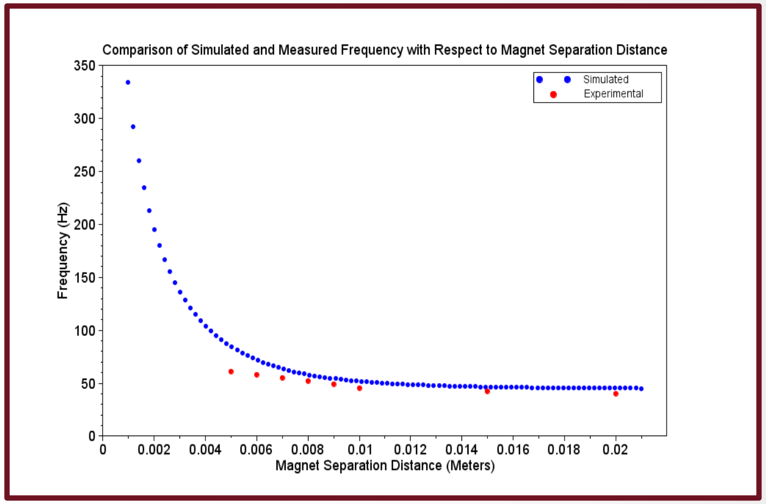
by Davison and Mo (2013)



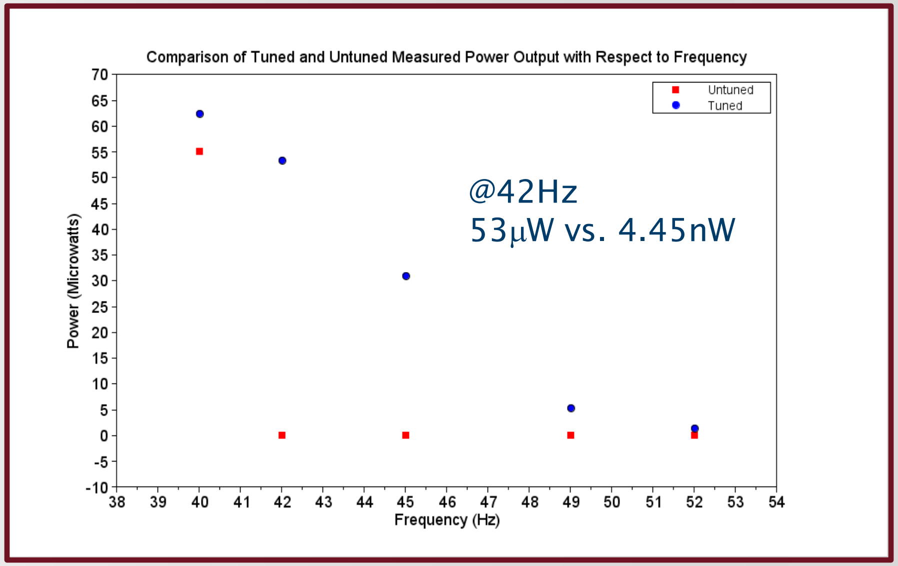
Schematic of experimental set-up for tuning the energy harvester



Experimental set-up



Frequency vs. magnet separation distance



Tuned vs. untuned power output

Conclusion

- **Relatively recent energy harvesting technologies for SHM of machinery, civil, and aerospace applications are reviewed.**
  - **Most common ambient energy sources – vibrations, wind, rotational kinetic energy, and thermal and solar energy - used for SHM are briefly overviewed.**
  - **Introductory survey of some frequency tuning methods is also conducted.**
- **Energy harvesting is one of major components of SHM system.**
- **Development of stand-alone, self-powered wireless sensor nodes for SHM systems will be expanding broader and spreading far more in the future.**

WASHINGTON STATE UNIVERSITY
TRI-CITIES
World Class. Face to Face.

Questions!