SMART MATERIAL
Advanced Piezo Composites

Low frequency, non resonant energy harvesting using piezo ceramic Macro Fiber Composites

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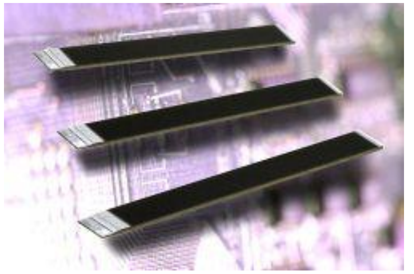
Outline

- Introduction
  - Vibration energy Harvesting with low profile piezo ceramic actuators
  - ALPA family
  - Typical EH operational modes
- Motivation for Low Frequency Vibration Harvesting with ALPAs
- Design considerations using ALPAs in Low Frequency Applications
- Conclusion

Piezo Ceramic Vibration Harvester

- Piezo bulk ceramic Bi- and Tri-morphs used for more than 25 years in vibration harvester
- Bi- and Tri-morphs mostly used in resonance mode applications
- Electromagnetic harvester are normally outperforming bi- and tri-morph ***bulk*** ceramic harvester, especially in low frequency applications due to
  - price
  - reliability, lifetime
  - low impedance in non-resonant or low frequency applications, yielding higher output
  - availability



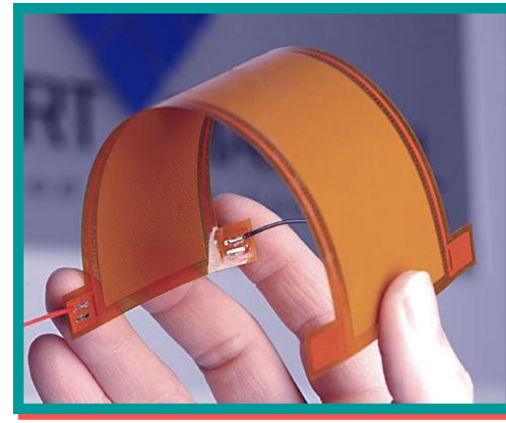
Photos courtesy Morgan Electro, EnOcean

New Piezo Vibration Harvester

- Starting by the end of 1999 new piezo ceramic based products and technologies became commercially available which were quickly used for vibration harvester as well:
  - ***Piezo ceramic composites in form of an Advanced Low Profile Actuator (ALPA)***
  - MEMs
  - Magneto strictive devices
  - Thin film piezo ceramic devices
- Focus on Macro Fiber Composite as a member of the ALPA family which are improving the application envelope compared with bulk bi- and tri-morphs in vibration harvester

MFC – excellent match for vibration energy harvesting

- MFC – Macro Fiber Composites developed at NASA LaRC during the late `90s
- **Actuator** (1Hz to 10kHz)
- **Sensor** (0.5 Hz up to 500kHz)
- **Flexible** and **robust**, ready to use package, overcomes disadvantages of solid PZT plates or patches based on solid wafers
- **Reliable**, > **10^9** cycles as actuator and > **10^{10}** cycles for energy harvesting
- Broadband, allows for easy **non-resonant** and **resonant** energy harvesting applications
- Encapsulated and fault tolerant
- Integration of electronic components possible

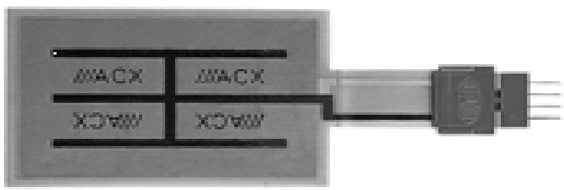


design award 2005

ALPA Types and Development History

THUNDER

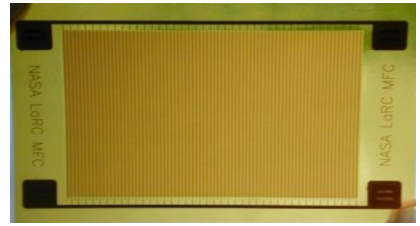
THin layer **UN**imorph **Driv****ER**



AFC

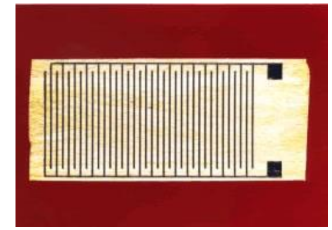
Active **F**iber **C**omposite

MFC

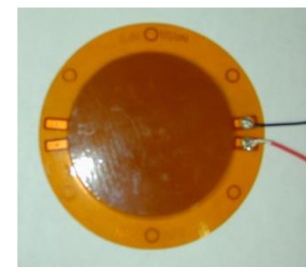


Macro**F**iber **C**omposite

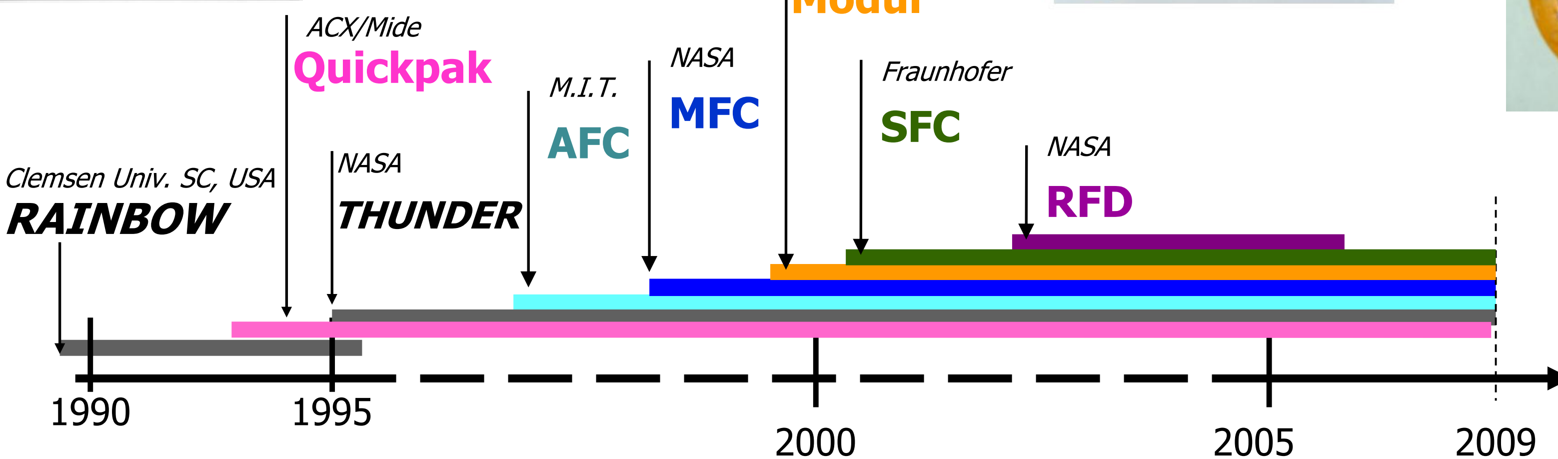
SFC



RFD



Radial **F**ield **D**iaphragm

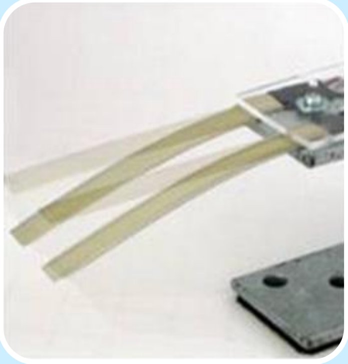


Photos courtesy NASA, CCC, ACX, DLR, Fraunhofer

ALPAs overcome many problems - but not all

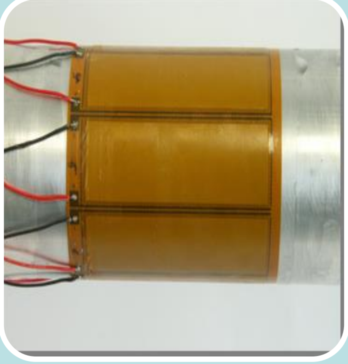
- Improvements for Vibration Harvester over existing bulk ceramic Bi-, Tri-morphs
  - flexibility,
  - allow for easy non-resonant applications
  - durability, lifetime extended for up to 10^{10} cycles, critical to advance over batteries or electro magnetic
  - low profile, easy integration
- Remaining disadvantages
  - price (getting better though)
  - high electric impedance, especially at < 5 Hz

Resonant vs. Non-resonant Vibration Harvesting



Resonant – mechanical transfer of vibration by Cantilever

- Acceleration (G's) and frequency main design input
- Use of mechanical structure for energy transfer allows to adapt operation for prevalent vibration frequency
- Optimum energy harvesting at discrete frequencies only
- Often bulky device, not suitable for large frequency range



Non Resonant - directly attached to strain area

- Strain and frequency is main design input
- Piezo harvester is attached directly to maximum strain – area, very small mechanical harvester possible
- Normally not operating at resonance – lower yield
- Capable of harvesting from broad frequency spectrum

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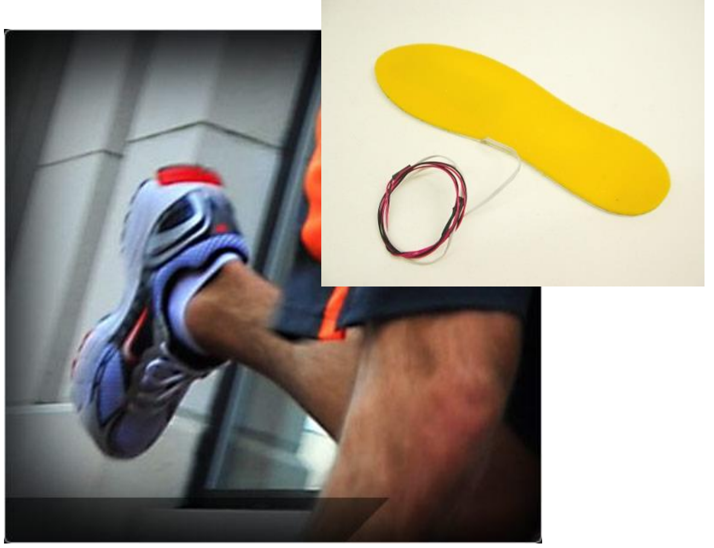
Low Frequency = Electromagnetic harvester?

- Low frequency < 5 Hz
- Most of the low frequency vibration harvesting applications are using electromagnetic systems.
- What advantages over electromagnetic systems do ALPAs have?
  - dimensions, low profile
  - easy mechanical integration, flexible, can be directly attached to a node of vibration
  - higher stiffness, requires lower deflection
  - typical lower deflection rates sufficient
  - weight
  - no mechanical moving parts, can be made fully solid state

Low Frequency Application for ALPAs

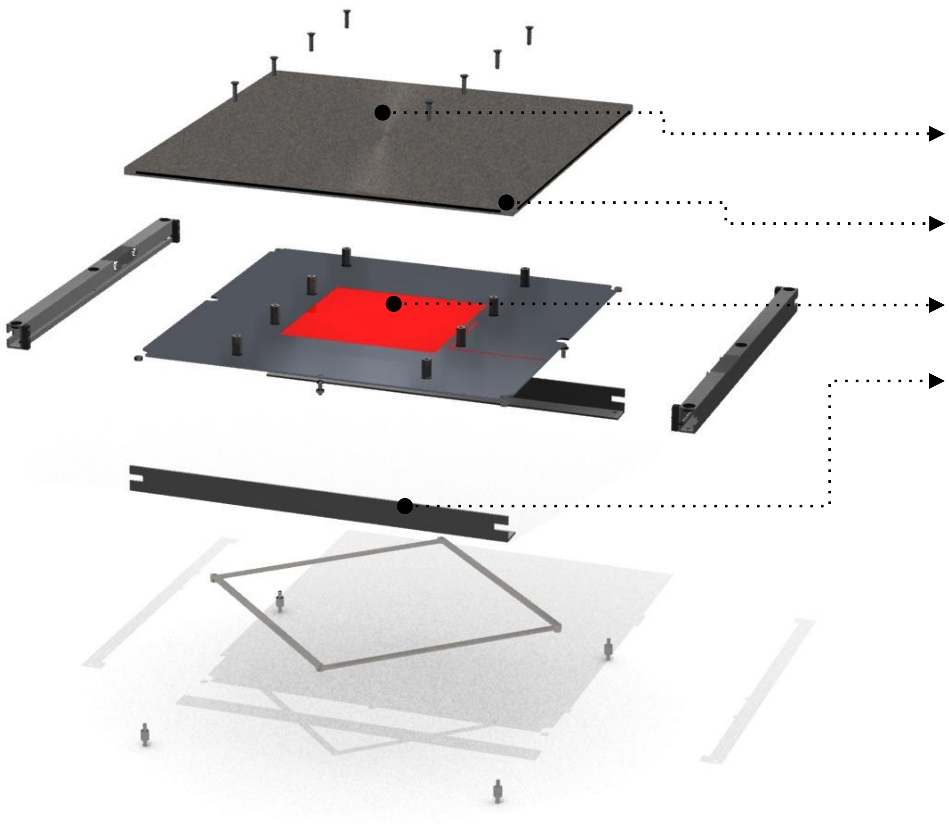
- Insole for shoes
  - requiring small profile
  - encapsulation, waterproof
  - long lifetime

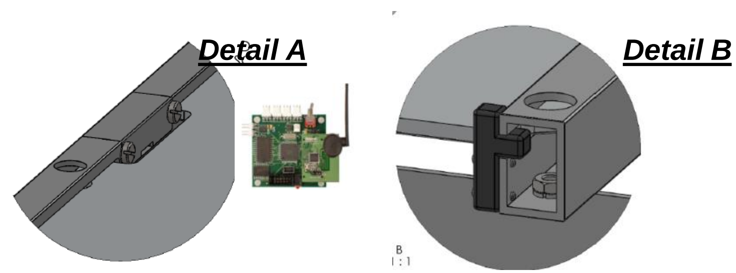


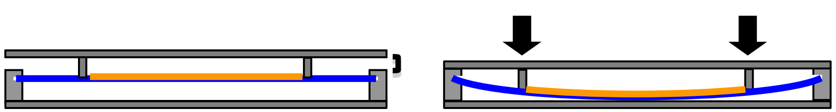
- Chest band/Shirt
  - translating breathing motions

    in bending of a structure for harvesting

Smart Tile from POWERleap







CIVIONICS POWERleap™

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Vibration Harvester – Typical Design & Challenge

Vibration Harvester – ALPA, non-resonant integrated in structure, low frequency, intermittent use

Conditioner - Integrated Energy Management Rectifier, Impedance Matching, Energy Storage, Stabilizer

Electronic Consumer - Sensor, Amplifier, Micro Controller, Radio Transceiver

E-module match, Strain optimization (neutral fiber, frequency, distribution), size

Charge Output

Custom designed Conditioner for low frequency mandatory, due to high electric impedance mismatch

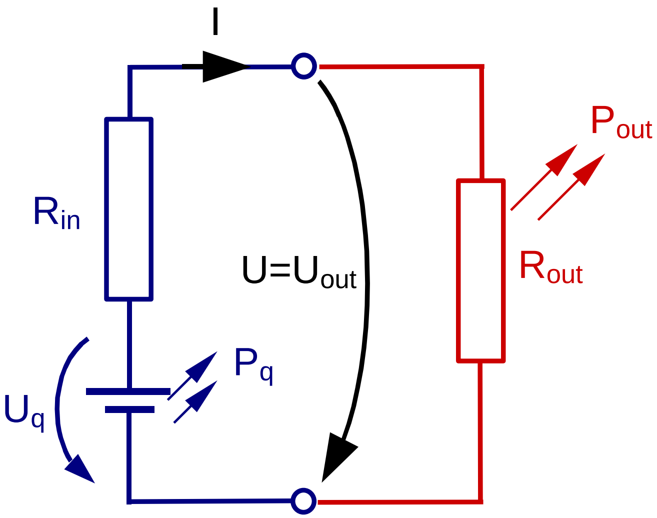
Power Consumption over time, operating voltage

Design Challenges to meet

Low frequency < 5Hz and intermittent (not periodic) charge generation have specific design challenges for maximum charge extraction

- High internal impedance, paired with intermittent events require a charge coupled design for best and cost effective charge extraction
- In a clamped condition, strain distribution needs to be addressed with triangle shaped designs to prevent asymmetric charge distribution
- Maximum strain and dependant depolarization limits have to be considered

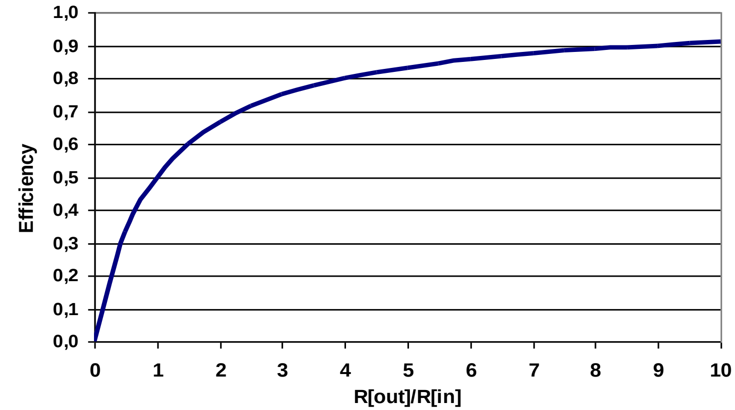
Basics of power transfer in active dipoles - Compromise



Efficiency

$$\eta = \frac{P_{out}}{P_q} = \frac{R_{out}}{R_{in} + R_{out}}$$

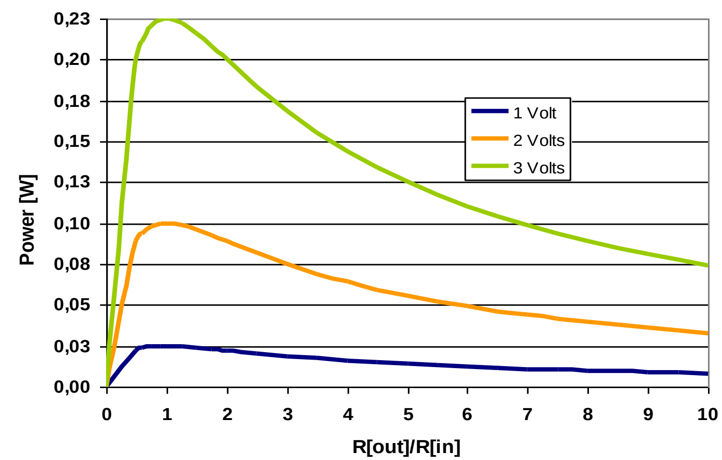
$R_{out} >> R_{in}$



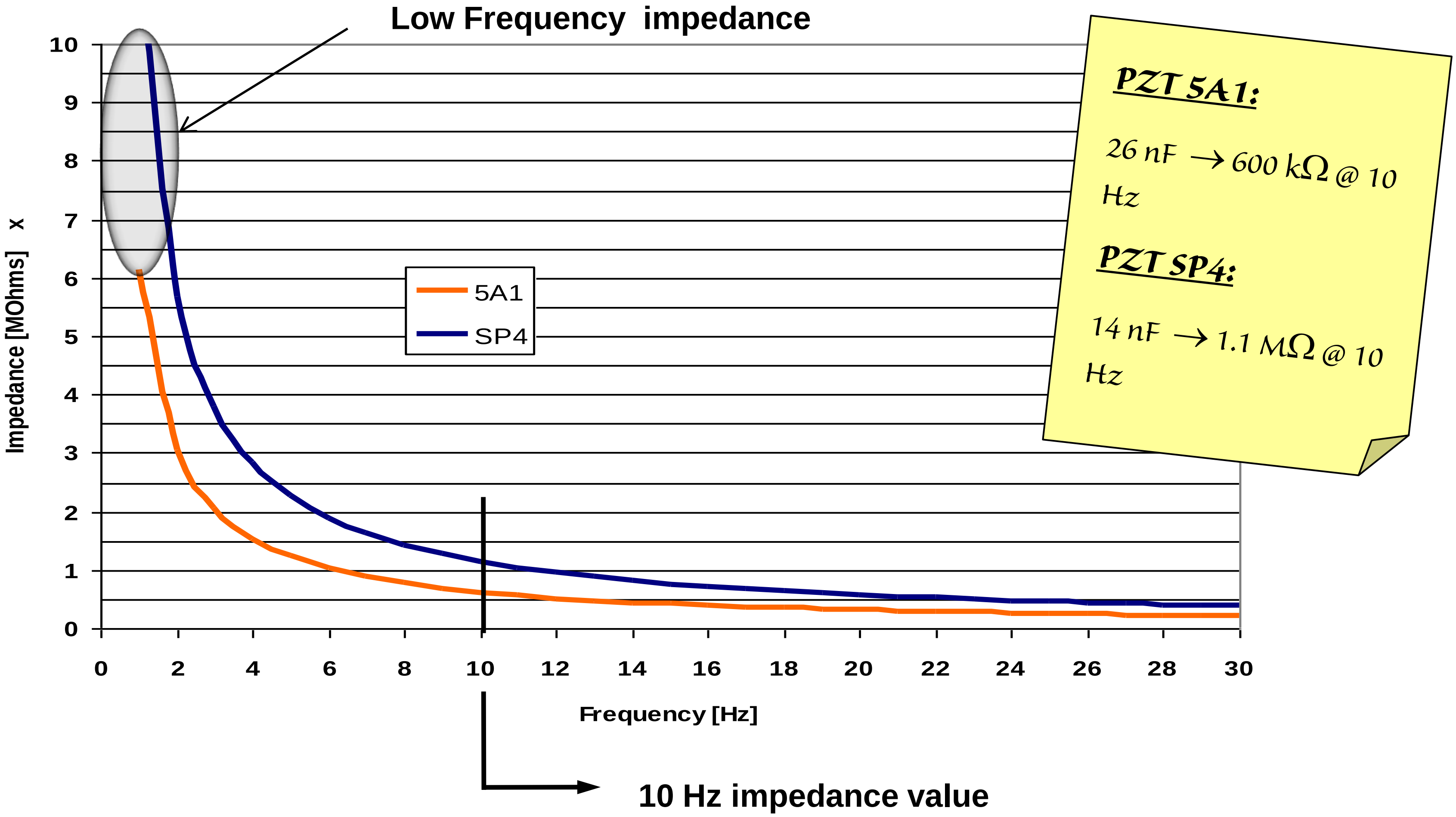
Energy Transfer

$$P_{out} = U_q^2 * \frac{R_{out}}{\left(R_{in} + R_{out}\right)^2}$$

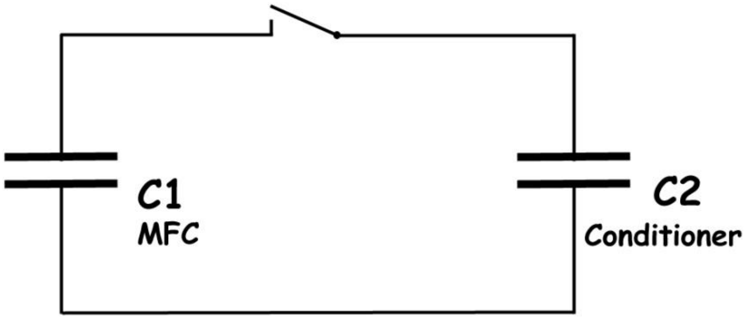
$R_{out} = R_{in}$



Dynamic impedance behavior for MFC M2814P2



Cap to Cap Energy Transfer Loss Problem



With $Q = CU$ and $E = \frac{1}{2} C \cdot U^2 \Rightarrow$

$U_{C1+C2} = \frac{1}{2} U_{C1}$

Energy in C1 and C2 after closing switch = 25% each,

25% is maximum energy extraction!

C1 = C2 optimum energy transfer

Voltage	20	**V**
C1	170	**nF**

8528-P2

C1-C2 ratio		**0.01**	**0.02**	**0.05**	**0.1**	**0.2**	**1**	**2**	**5**	**10**	**20**	**50**	**100**
C2	**nF**	**1.7**	**3.4**	**8.5**	**17**	**34**	**170**	**340**	**850**	**1700**	**3400**	**8500**	**17000**
Initial charge in C1	As	3.4E-06	3.4E-06	3.4E-06	3.4E-06	3.4E-06	3.4E-06	3.4E-06	3.4E-06	3.4E-06	3.4E-06	3.4E-06	3.4E-06
Initial energy in C1	mWs	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034	0.034
Voltage after switching	V	19.80	19.61	19.05	18.18	16.67	10.00	6.67	3.33	1.82	0.95	0.39	0.20
Charge in C2	As	3.4E-08	6.7E-08	1.6E-07	3.1E-07	5.7E-07	1.7E-06	2.3E-06	2.8E-06	3.1E-06	3.2E-06	3.3E-06	3.4E-06
Energy in C2	mWs	0.00033	0.00065	0.00154	0.00281	0.00472	0.0085	0.00756	0.00472	0.00281	0.00154	0.00065	0.00033
Energy C2 % of initial	**%**	**1.0**	**1.9**	**4.5**	**8.3**	**13.9**	**25.0**	**22.2**	**13.9**	**8.3**	**4.5**	**1.9**	**1.0**
Energy in C1 after switch.	mWs	0.03333	0.03268	0.03084	0.0281	0.02361	0.0085	0.00378	0.00094	0.00028	7.7E-05	1.3E-05	3.3E-06
Total Energy after switch	mWs	0.0337	0.0333	0.0324	0.0309	0.0283	0.0170	0.0113	0.0057	0.0031	0.0016	0.0007	0.0003
Total Energy as % of initial	%	99.01	98.04	95.24	90.91	83.33	50.00	33.33	16.67	9.09	4.76	1.96	0.99

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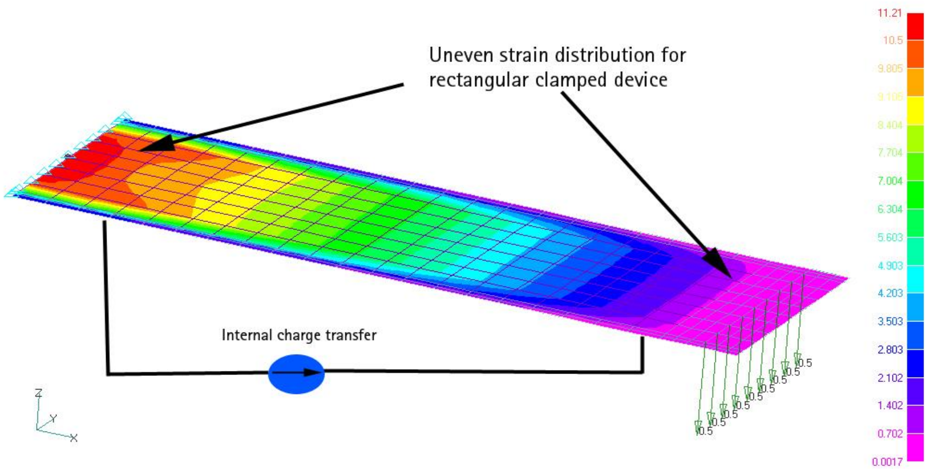
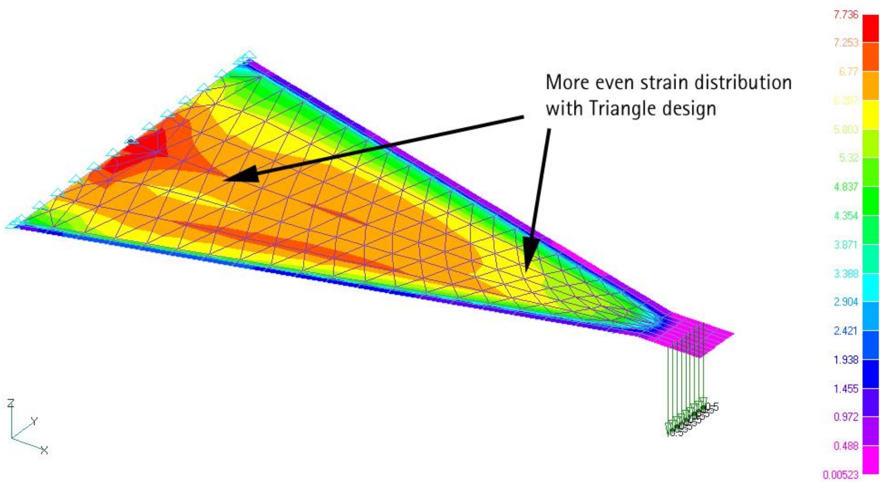
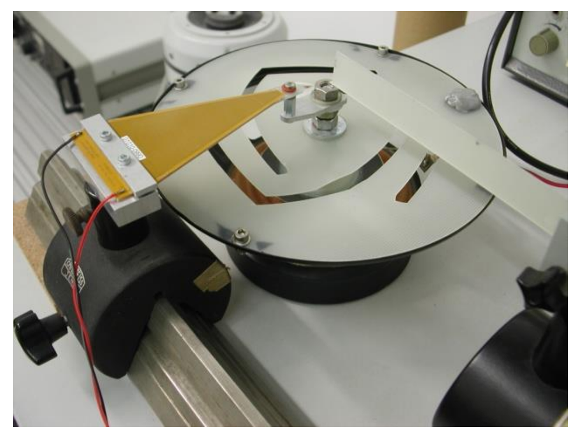
Charge transfer in clamped device – shape counts



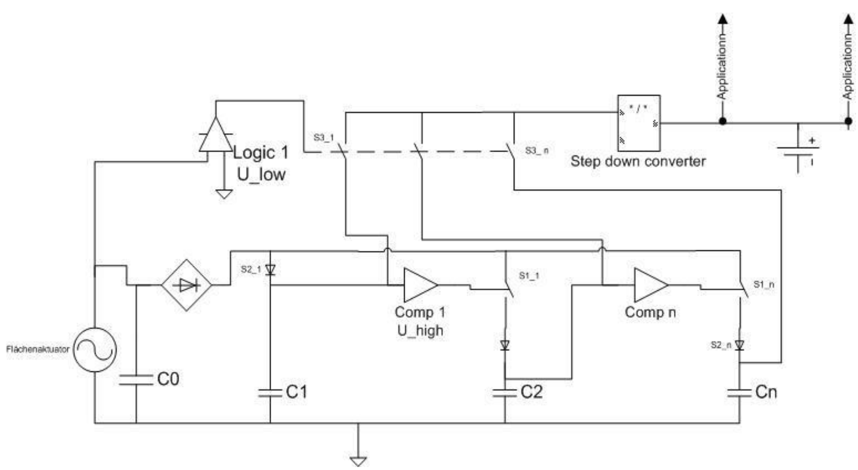


- Rectangular mechanically clamped PZT harvester result in uneven strain distribution over length
- this might cause device internal charge transfer between different areas of strain and lower the overall charge extraction
- triangle shaped PZT harvester are improving the strain distribution and overall charge extraction



Low Frequency Conditioner EH-CL50

- Standard PZT Conditioners now available as chipsets or standard circuit DO NOT imply good performance for low frequency/intermittent harvester applications!
- EH-CL50 special developed piezo ceramic conditioner for P2-type MFCs for low frequency/intermittent harvesting applications
- Based on capacitive energy extraction
- automatic capacitance switching and impedance matching



Conclusions

- Low profile piezo composite actuators (ALPA) are significant improvement over standard PZT bi- and tri-morphs in vibration energy harvesting applications.
- ALPA have advantages for non-resonant energy harvesting by applying them directly to vibration nodes.
- In low frequency, intermittent modes ALPAs have advantages over normally used electromagnetic systems, especially if weight, dimensions are critical and a non-moving parts design is important.
- Intrinsic high impedance of piezo ceramic harvester at low frequencies require special designed Conditioner circuits, normally charge coupled designs (cap to cap) for size and cost reasons.
- Off-the-shelve conditioners and harvester chipsets are not implicitly efficient in low frequency harvesting applications.
- Cap-to-cap designs limit maximum energy extraction to 25%, in general total system performance is more near 10-15% of initial PZT generated energy compared with 25-35% for resonant, periodic systems.
- Due to the lower efficacy of low frequency ALPA systems, an even strain distribution in the harvester for optimum charge generation is mandatory (triangle design)