Applikationen mit dem Piezokompositwerkstoff MFC – Energie aus Vibrationen für die Übertragung von Telemetriedaten

Thomas Daue, Jan Kunzmann
Smart Material Corp.

Überblick

- Einführung
  - Firma und Produkte
  - Piezoeffekt und Piezokomposite
  - ALPAs = Advanced Low Profile Actuators
- Anwendungsbeispiele in den letzten Jahren
- Niederfrequente Vibrationsharvester mit ALPAs.
  - Probleme und Designhilfen

Smart Material Group - History

- Smart Material Corporation with its affiliated company Smart Material GmbH is developing and manufacturing piezo-composite materials. Piezo-composites are part of the group of new materials or smart materials.
- Founded in 2000 Smart Material has become a major supplier of piezo-composite materials, which are assembled into components and complete systems by its customers. Our mission: To provide advanced piezo composites for commercial applications in high quantity, high quality and low cost.

Intelligente Werkstoffe formen unsere Zukunft.
Anpassungsfähig. Schnell. Zuverlässig.

Smart Material Group – Locations

Smart Material Corp.
1990 Main Street;Suite 750
Sarasota, FL 34236
U.S.A.

Smart Material GmbH
Löbtauer Str. 69
01159 Dresden
Germany

Trek Japan K.K
Mr. Yuichi Koiwa-san
Meguro-ku;
Tokyo 141-0013; Jp

Smart Material Group - Products

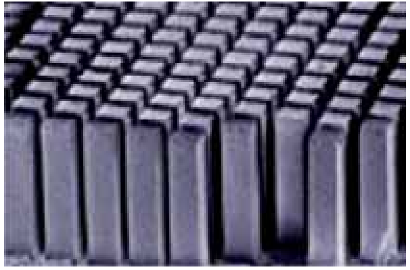
Piezo-Fibers

- 100 – 800 µm Diameter
- PZT NAVY types II, III, IV und VI
- tubes with diameters of 400-1000 µm

1-3 Piezo Composites

- arrange & Fill
- frequency range 25 kHz – 6 MHz
- fiber fill factor 25% - 65 %
- discs up to 3“ or rectangular plates
- random or regular fiber distribution
- array-designs

1-3 Softmold Composites

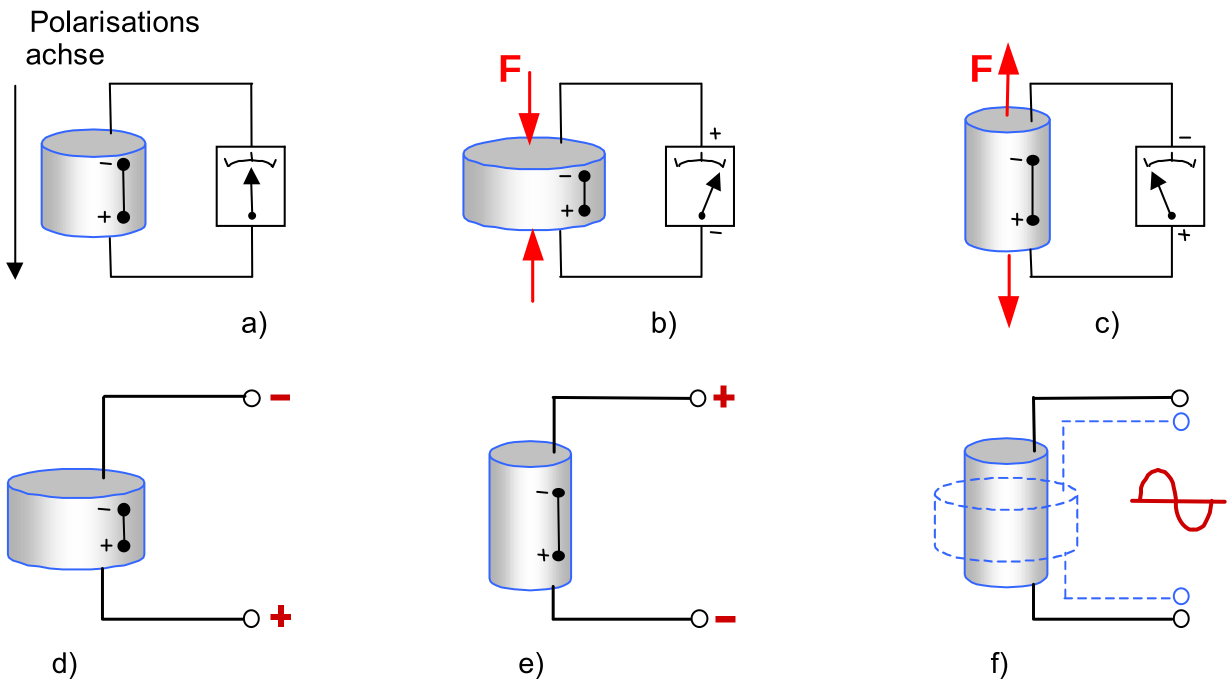


- frequency range 3,5 MHz – 10 MHz
- possible Pixel size 35 µm – 100 µm
- round, triangular or rectangular Pixel cross-section

Macro Fiber Composites

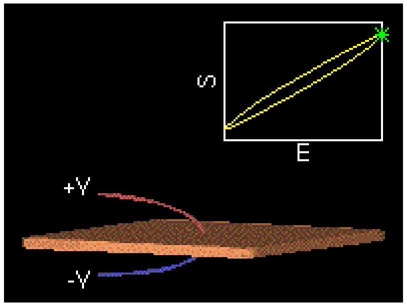
- 12 different Standard-Types
- types using the d_{33} or d_{31} Effect
- customized Layouts within 5 weeks
- fabrication licensed by NASA

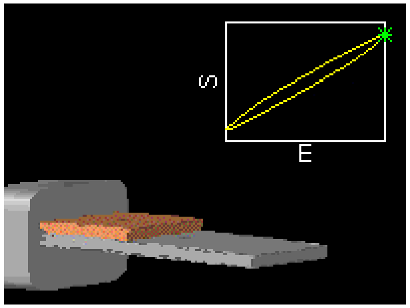
Direct and inverse Piezo-Effect

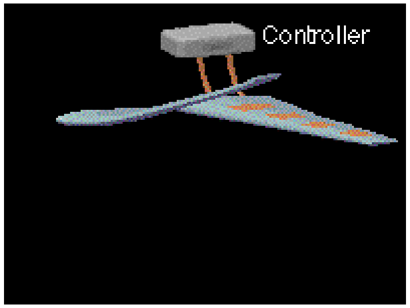


direct Piezo-Effect

inverese Piezo-Effect

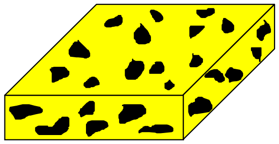


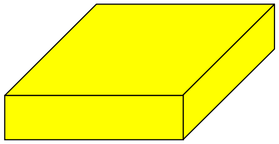


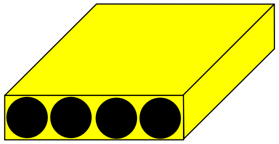


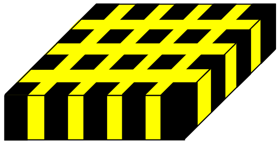
First Piezo-Composites in the ´70s

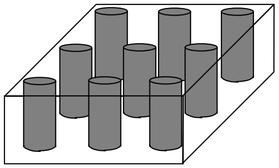
- First piezo composite was a rubber piezo-ceramic composite built in ’70s
- Classification of different types of piezo composites first introduced by R.E. Newnham et al. (PennState)

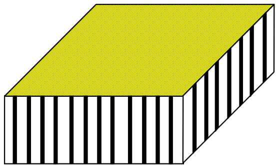

Partikel in einem Polymer
(0 - 3)

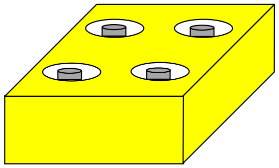

PVDF-Komposit
(0 - 3)

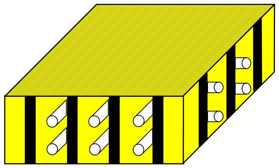

PZT-Fasern in einem Polymer
(1 - 3)

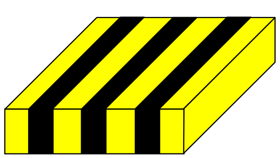

Würfel-Komposit
(1 - 3)

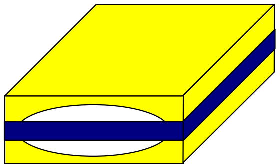

PZT-Stäbe in einem Polymer
(1 - 3)

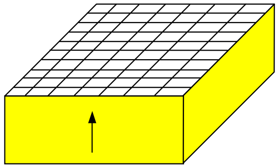

Glas-Keramik-Komposit
(1 - 3)

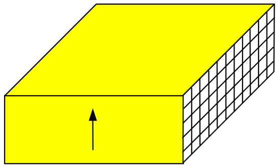

Keramik-Luft-Polymer-Komposit
(1 - 1 - 3)

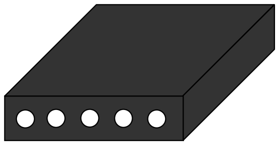

transversal verstärkt
(1 - 2 - 3)

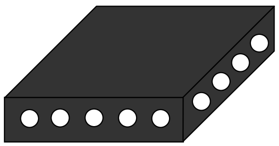

Schicht-Komposit
(2 - 2)

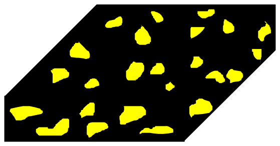

Moonie
(3 - 0)

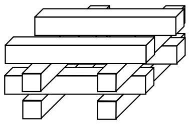

Bienenwaben-Komposit
(3 - 1P)


Bienenwaben-Komposit
(3 - 1S)

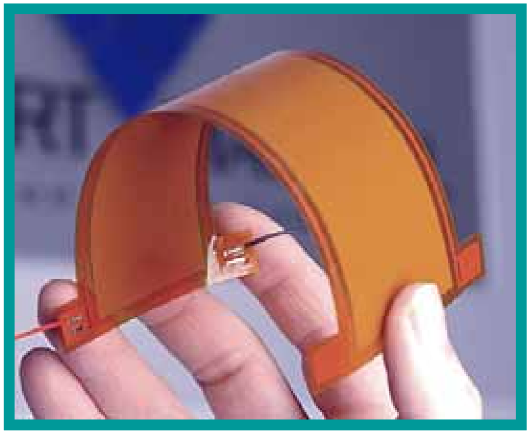

gelochter Komposit
(3 - 1)


kreuzgelochter Komposit
(3 - 2)

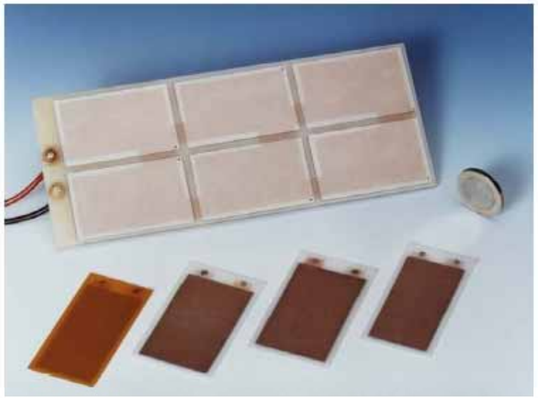

poröser, infiltrierter Komposit
(3 - 3)


Leiter-Komposit
(3 - 3)

ALPA – Advanced Low Profile Actuators



- Piezo ceramic based devices
- Thickness is a fraction of the width and length
  - "Patch" type
- Laminated and/or encapsulated
- Build-in fault tolerance against early failure
- Allows for easy integration into composite structures
- Electrical insulated to the environment
- Can be used as sensor and actuator

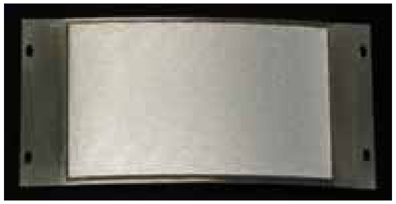


Developments started in 1989

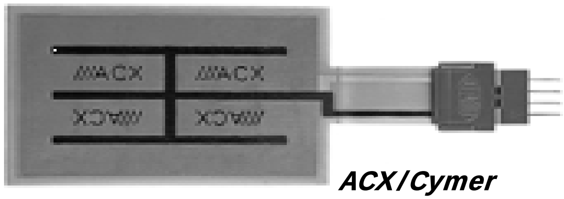
- First developments driven by aerospace and defense applications in the USA, funded by the DoD
- Targeted applications: Vibration control and Morphing (structural control)
- Goal was to overcome some of the shortcomings of PZT wafers and mono/bi-morphs
    - Improve reliability in high strain application
    - Encapsulation against environmental factors
    - Increasing strain (utilize also d_{33} effect)
    - Increase flexibility without sacrificing lifetime
    - Easy application and integration (in)to existing structures
    - Electrical insulation of contacts to allow for embedding in composite structures

History of ALPHA Developments

THUNDER



THin layer UNimorph DrivER

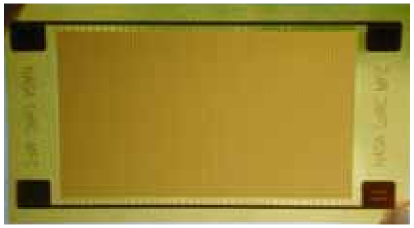


ACX/Cymer

AFC

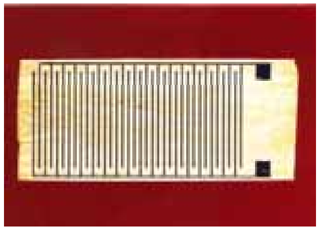
Active Fiber Composite

MFC



MacroFiber Composite

SFC



DLR

Funktions-Modul

RFD

Radial Field Diaphragm

ACX/Cymer

Quickpak

Clemsen Univ. SC, USA

RAINBOW

NASA

THUNDER

M.I.T.

AFC

NASA

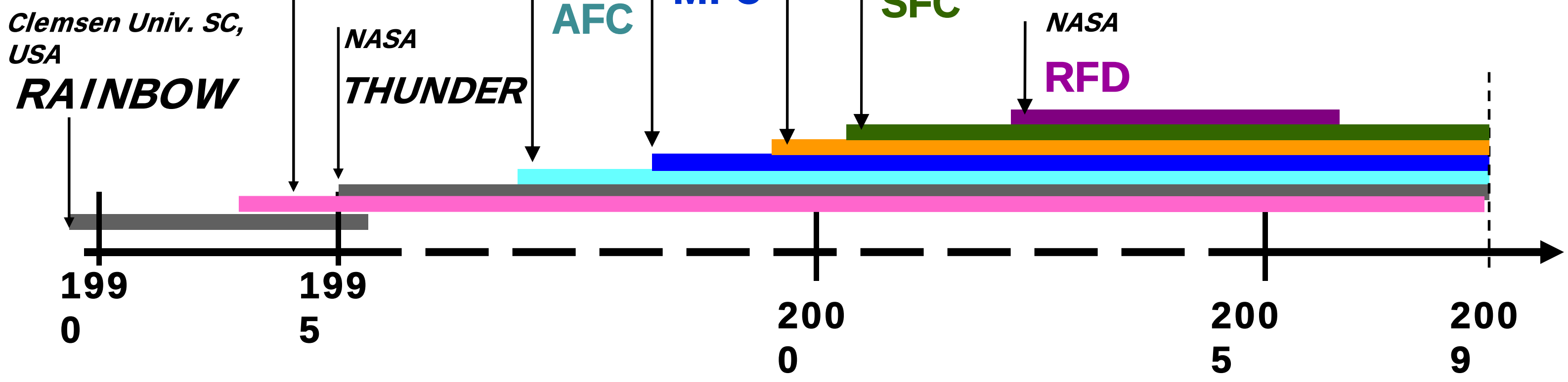
MFC

Fraunhofer

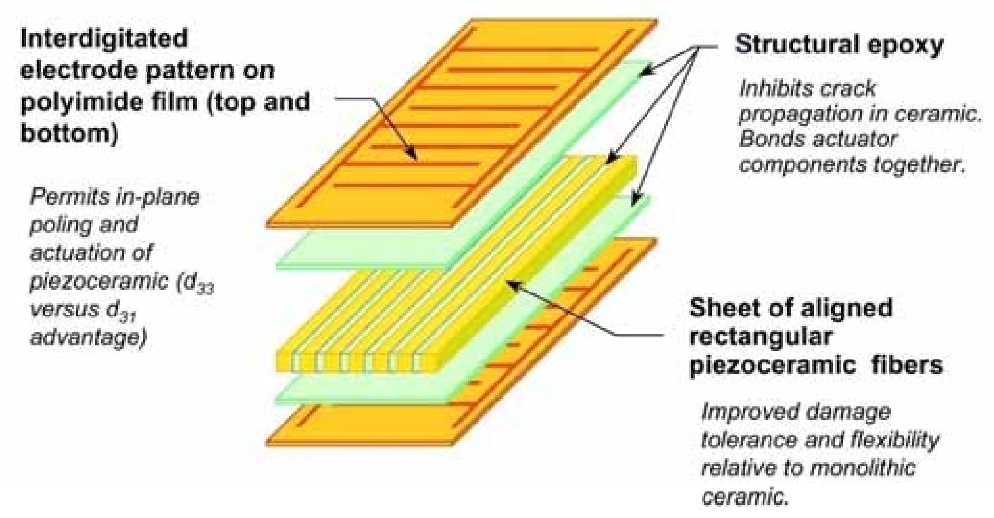
SFC

NASA

RFD



MFC – Principals of operation



Interdigitated electrode pattern on polyimide film (top and bottom)

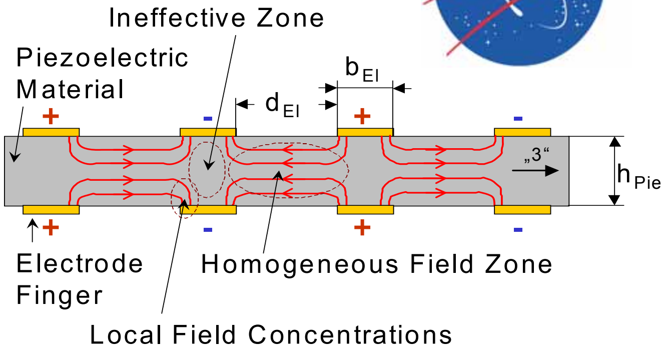
Permits in-plane poling and actuation of piezoceramic (d_{33} versus d_{31} advantage)

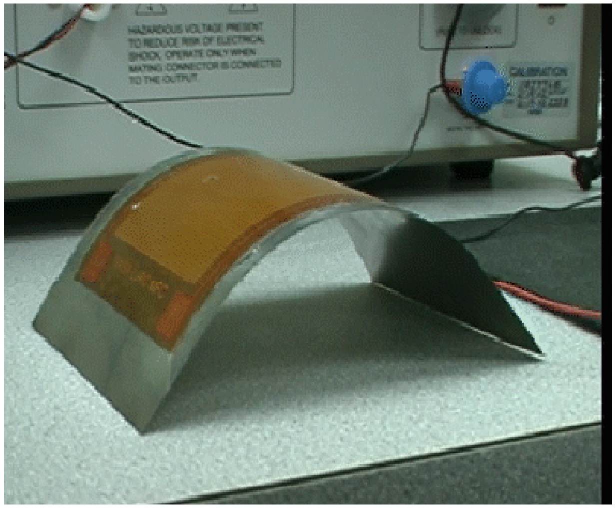
Structural epoxy

Inhibits crack propagation in ceramic. Bonds actuator components together.

Sheet of aligned rectangular piezoceramic fibers

Improved damage tolerance and flexibility relative to monolithic ceramic.



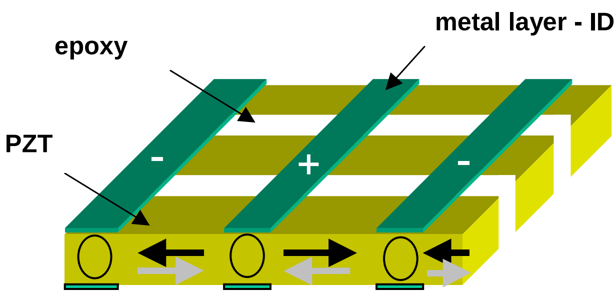


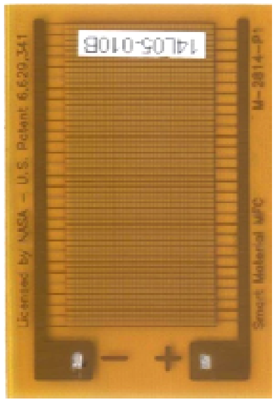
advantages:

- **flexibility**
- **conform to composite design**
- **usage of d_{33} in-plane**
- **anisotropic Sensor/Actuator**

Available MFC Types

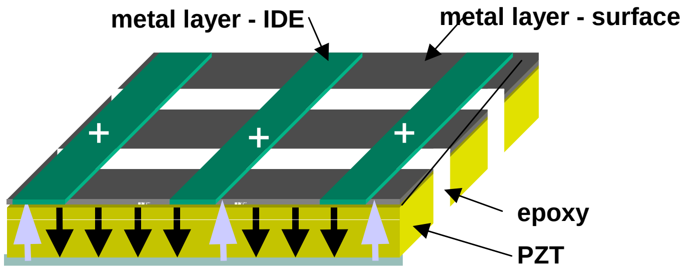
P1-Type MFC (d33)





Elongator

P2-Type MFC (d31)

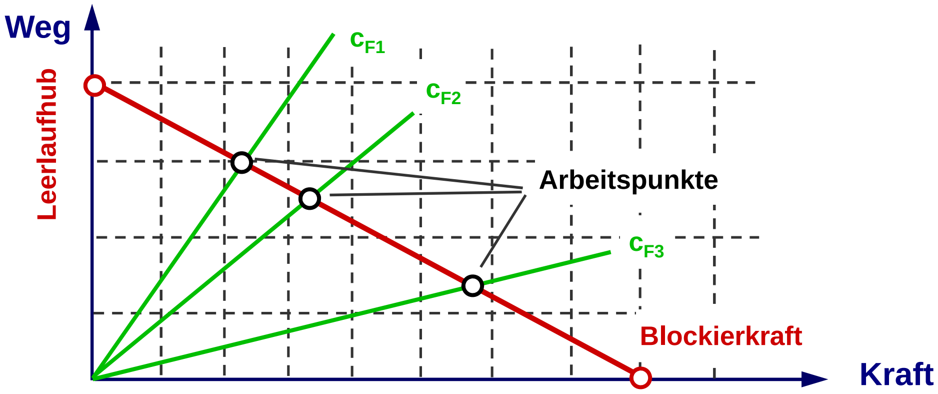


Contractor

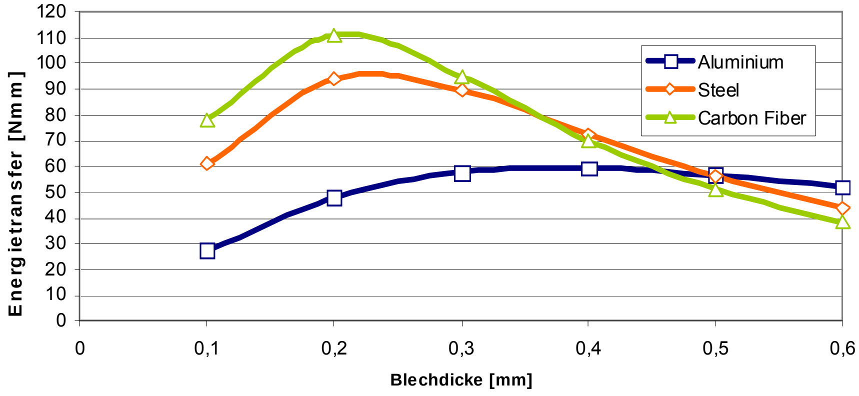
Device	Operation voltage		Capacity	Sensor characteristic		Actuator characteristic	Generator characteristic
	V_{op}^{+} [V]	V_{op}^{-} [V]	C_{pol} [nF / cm^2]	$d_{33}^{\ eff}$ [pC / N]	$d_{31}^{\ eff}$ [pC / N]	Strain / Volt. [µstrain / V]	Charge/Strain [pC / ppm]
3-3 MFC	**1500**	**-500**	**0,42**	**460**	**-**	**0,7..0,9** [0 … 1500V]	**1670** [> 100V]
3-1 MFC	**360**	**-60**	**4,5**	**-**	**-370**	**- 2** [0 … 360 V]	**3250** [< 100 V]

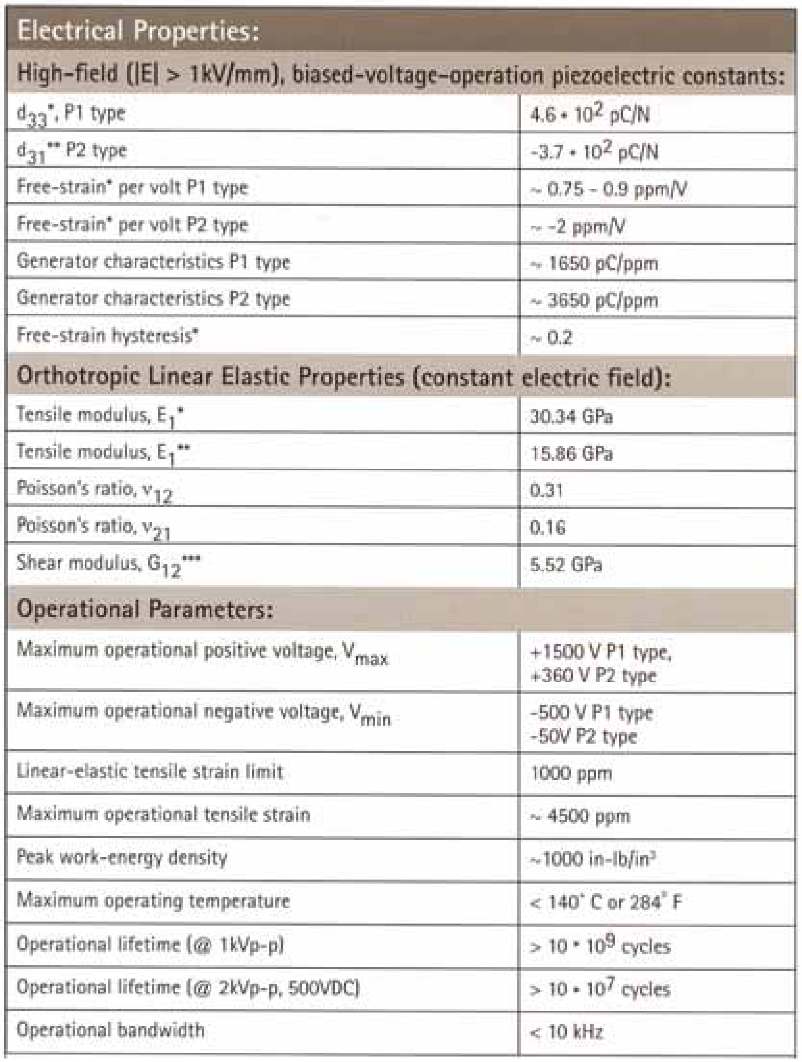
Basics for calculation

Work diagram



Optimal substrate thickness for max energy transfer

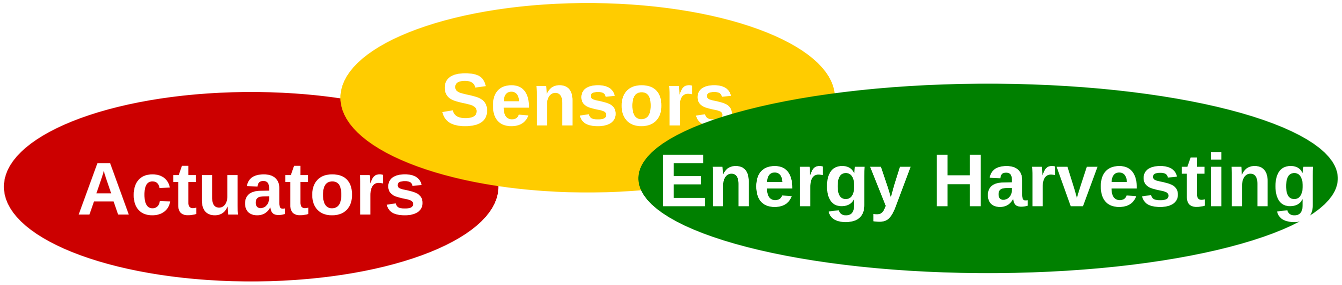




Electrical Properties:	
High-field (|E| > 1kV/mm), biased-voltage-operation piezoelectric constants:	
d_{33}*, P1 type	4.6 • 10^2 pC/N
d_{31}** P2 type	-3.7 • 10^2 pC/N
Free-strain* per volt P1 type	~ 0.75 - 0.9 ppm/V
Free-strain* per volt P2 type	~ -2 ppm/V
Generator characteristics P1 type	~ 1650 pC/ppm
Generator characteristics P2 type	~ 3650 pC/ppm
Free-strain hysteresis*	~ 0.2
Orthotropic Linear Elastic Properties (constant electric field):	
Tensile modulus, E_1*	30.34 GPa
Tensile modulus, E_1**	15.86 GPa
Poisson's ratio, v_{12}	0.31
Poisson's ratio, v_{21}	0.16
Shear modulus, G_{12}***	5.52 GPa
Operational Parameters:	
Maximum operational positive voltage, V_{max}	+1500 V P1 type, +360 V P2 type
Maximum operational negative voltage, V_{min}	-500 V P1 type -50V P2 type
Linear-elastic tensile strain limit	1000 ppm
Maximum operational tensile strain	~ 4500 ppm
Peak work-energy density	~1000 in-lb/in³
Maximum operating temperature	< 140° C or 284° F
Operational lifetime (@ 1kVp-p)	> 10 • 10^9 cycles
Operational lifetime (@ 2kVp-p, 500VDC)	> 10 • 10^7 cycles
Operational bandwidth	< 10 kHz

Überblick

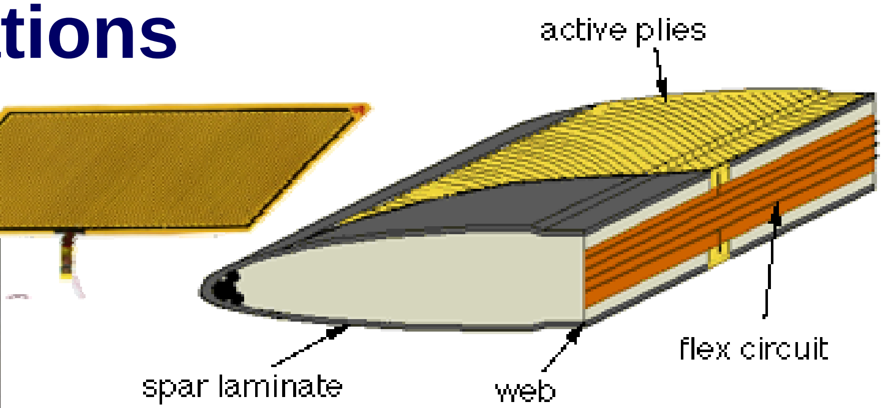
Anwendungen

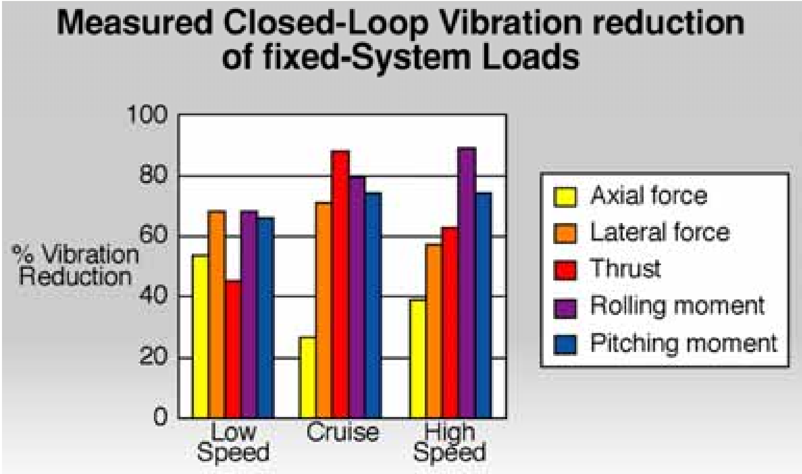

Sensors

Actuators

Energy Harvesting

Space & Aircraft Applications

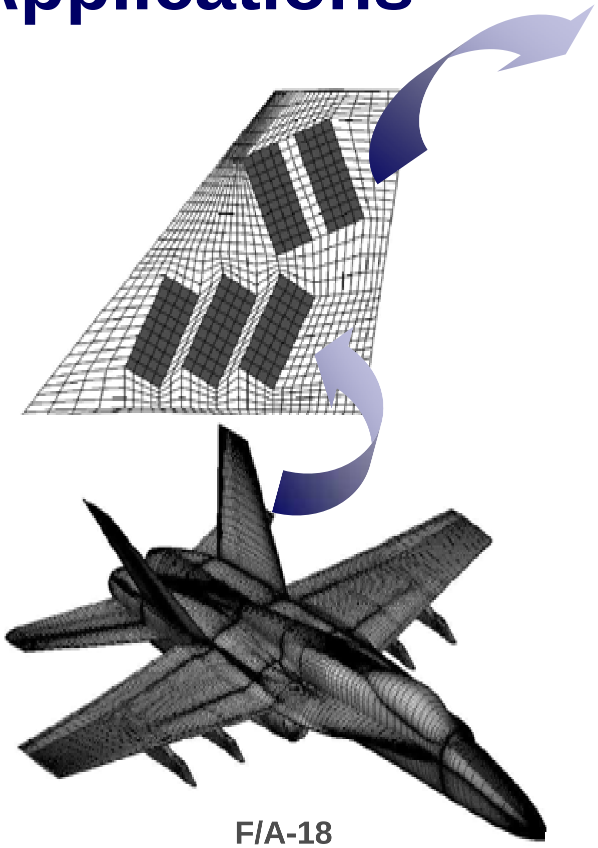




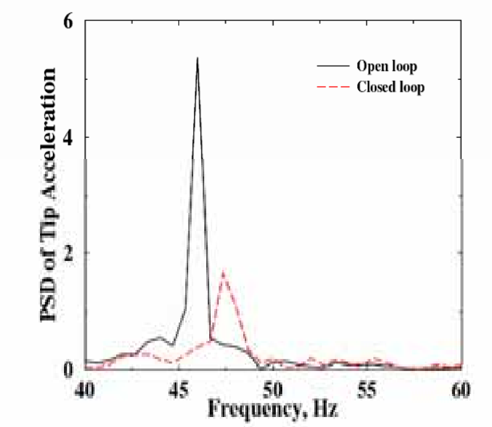
Active Twist Rotor (NASA, ARL, University of Michigan, Sikorsky)

Actuators

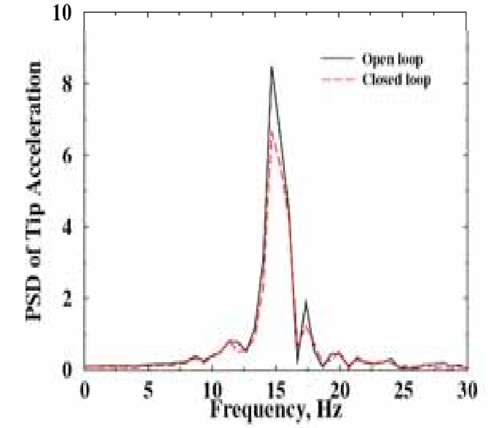
Space & Aircraft Applications



F/A-18



(b) PSD of tip acceleration at torsion mode

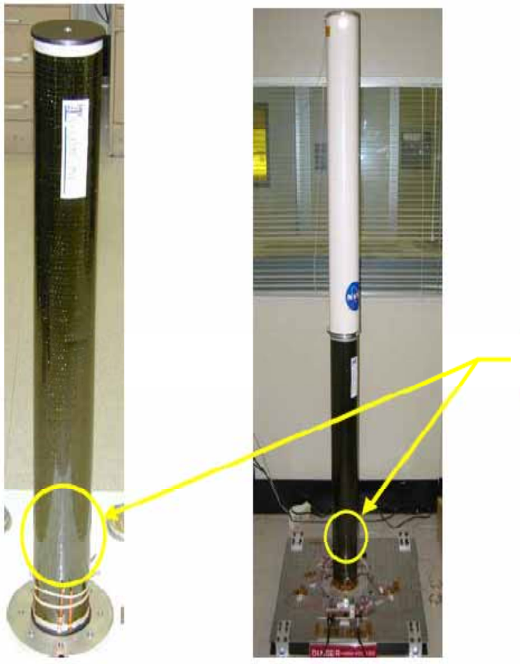


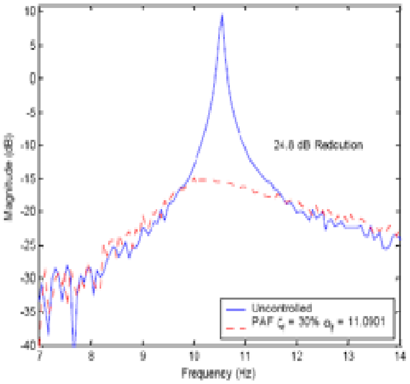
(a) PSD of tip acceleration at bending mode

Twin-tail buffet loads alleviation (NASA, AFRL, Boeing)

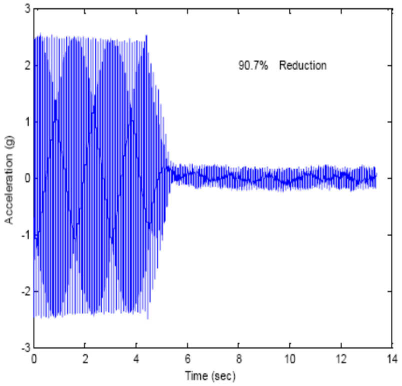
Actuators

Space & Aircraft Applications



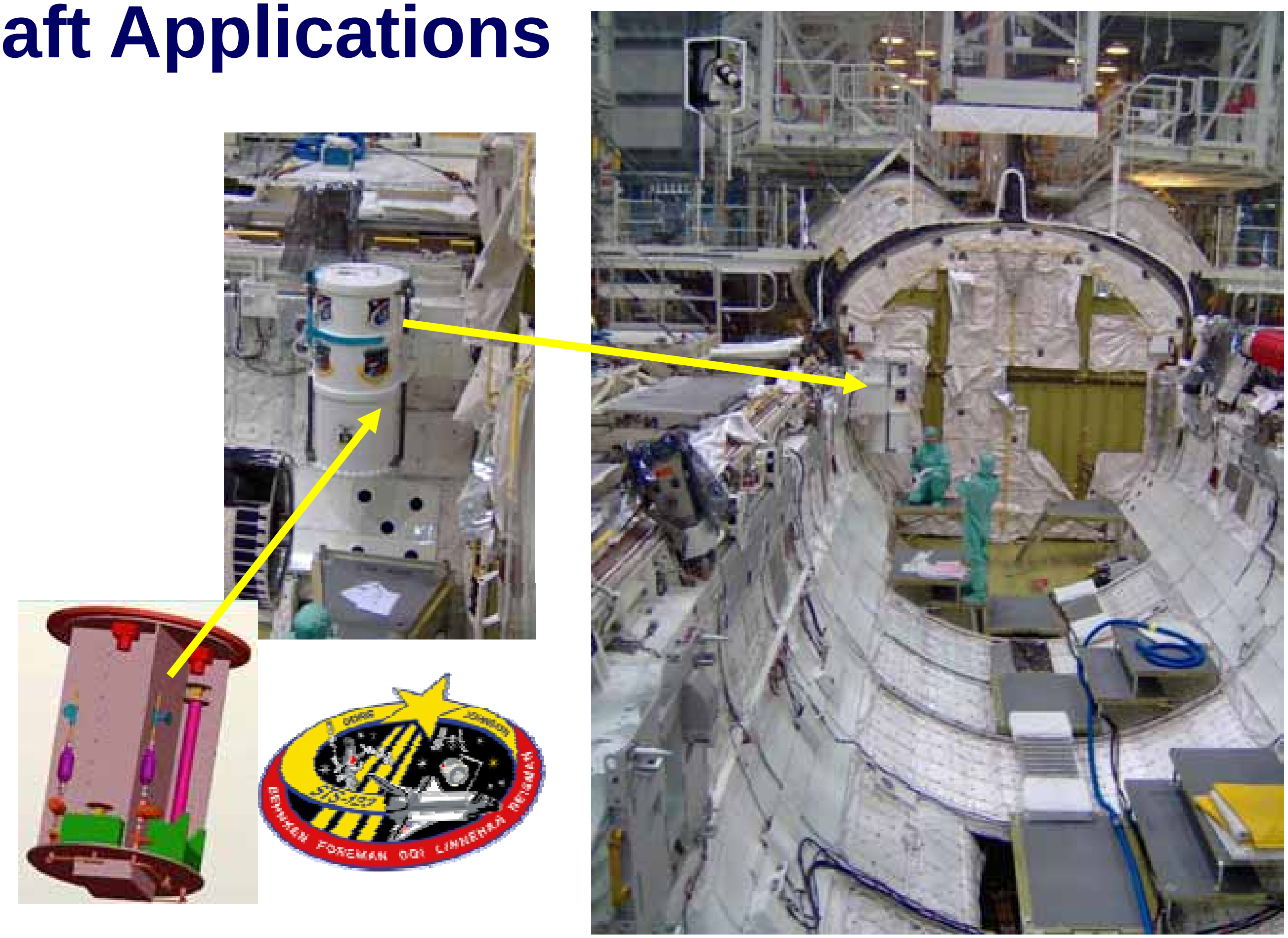


embedded MFC region



Active inflatable-rigidizeable spacecraft structures (NASA, JPL, DoD, L'GARDE, ILC Dover)

Space & Aircraft Applications

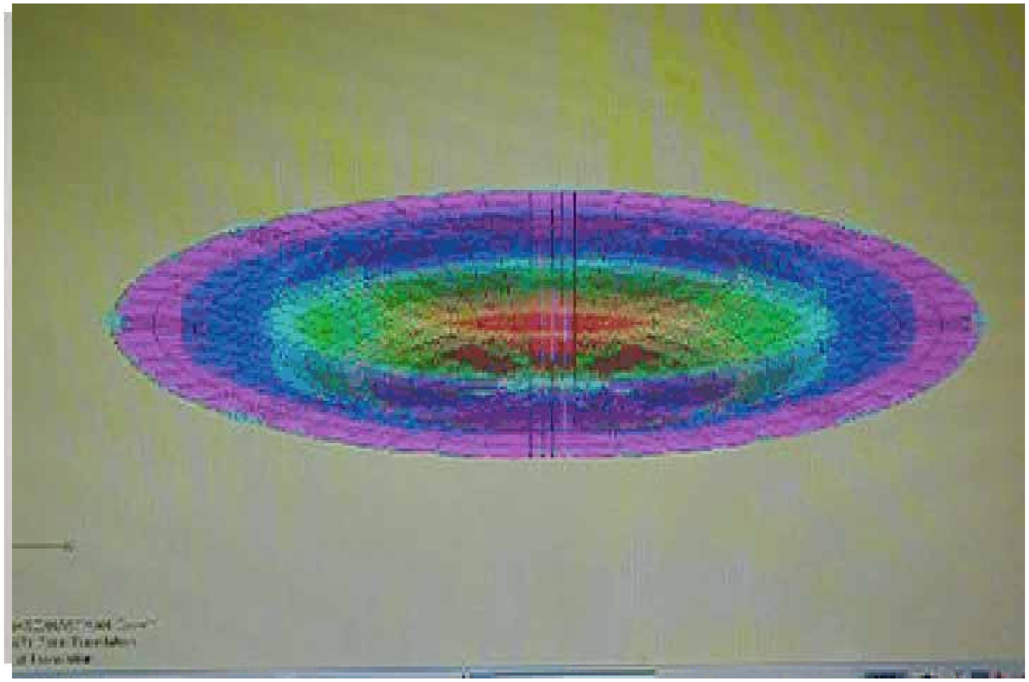


On-orbit rigidizeable structures dynamics Shuttle flight experiment (NASA, AFIT)

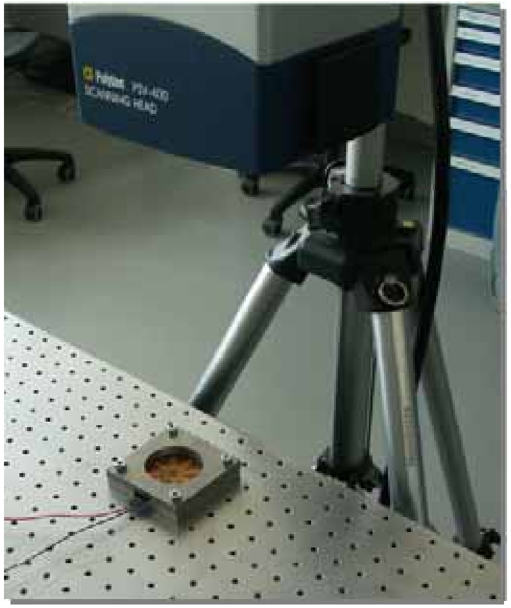
New star shaped MFC Actuator

Application in a membrane pump consisting of:

- **housing**
- **membrane**
- **2 valves**



membrane pump prototype

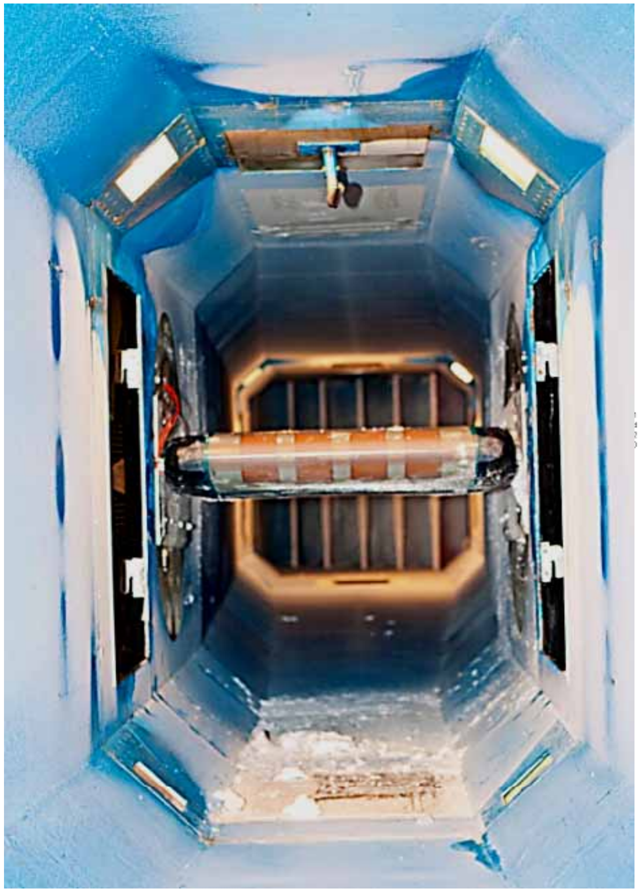


Laser vibrometric analysis

Actuators

Deicing System for the Predator Drone

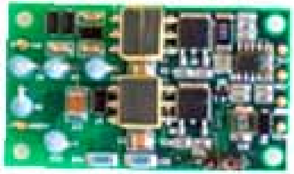
GENERAL ATOMICS
AERONAUTICAL



Photos courtesy GA-ASI, Patents Pending

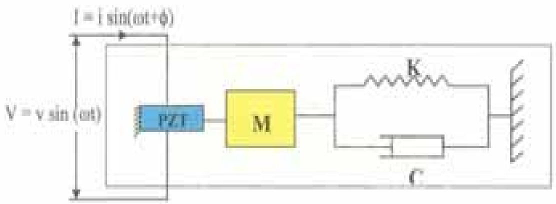
Fully solid state flight control for small

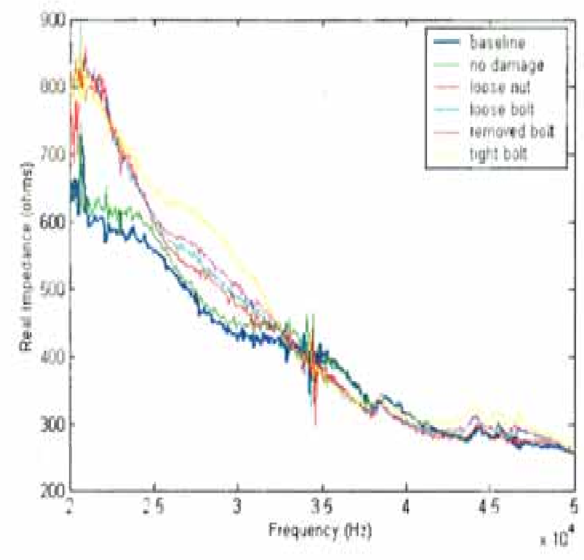
Photos courtesy SDI & Virginia Tech



AMD-2012-CE **battery operated power supply with analogue or PWM control input**

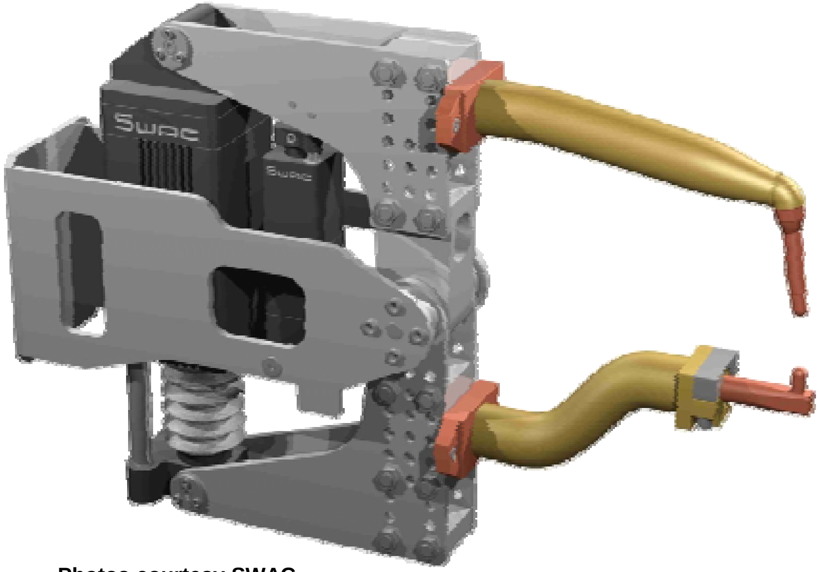
Space & Aircraft Applications





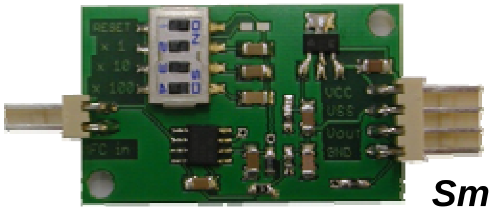
KSC launch tower white room impedance-based health monitoring (Virginia Tech, LANL),
KSC crawler bearing health monitoring (Virginia Tech, LANL),

Online spot welding quality control



Photos courtesy SWAC

- The MFC continuously senses the strain inside the arms of the spot welder
- Feedback loop with electric motor is controlling the pressure in real time
- Allow for welding with higher yield and new materials
- Improves yield of car body production and allow for welding of harder steels



SmartCharge^{TM}
low frequency piezo sensor electronic

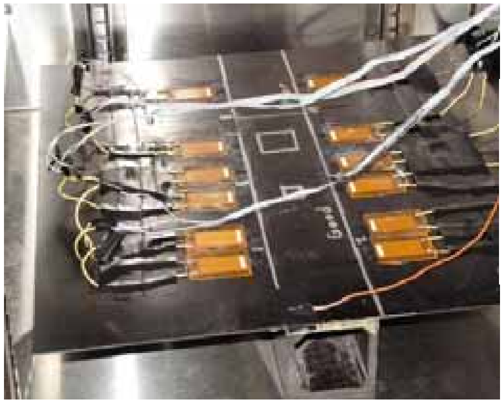
MFC as SONAR Transducer in towed arrays

Atlas Elektronik GmbH developed a SONAR transceiver based on the P1 type MFCs for towed arrays which has advantages over existing designs, due to

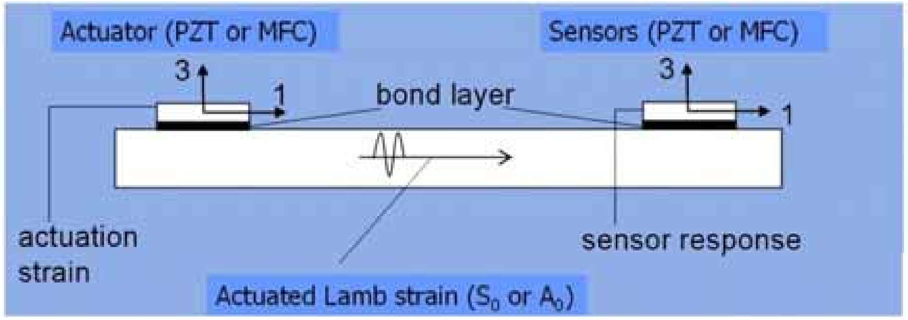
- Lower acoustic impedance to water compared with common Tonpilz or bulk ceramic designs
- Allow for smaller designs (smaller diameter) compared with traditional designs, saving space and weight

Photos courtesy Atlas Elektronik GmbH

Transducers for long range ultrasound inspection



UCSanDiego



WINTUR

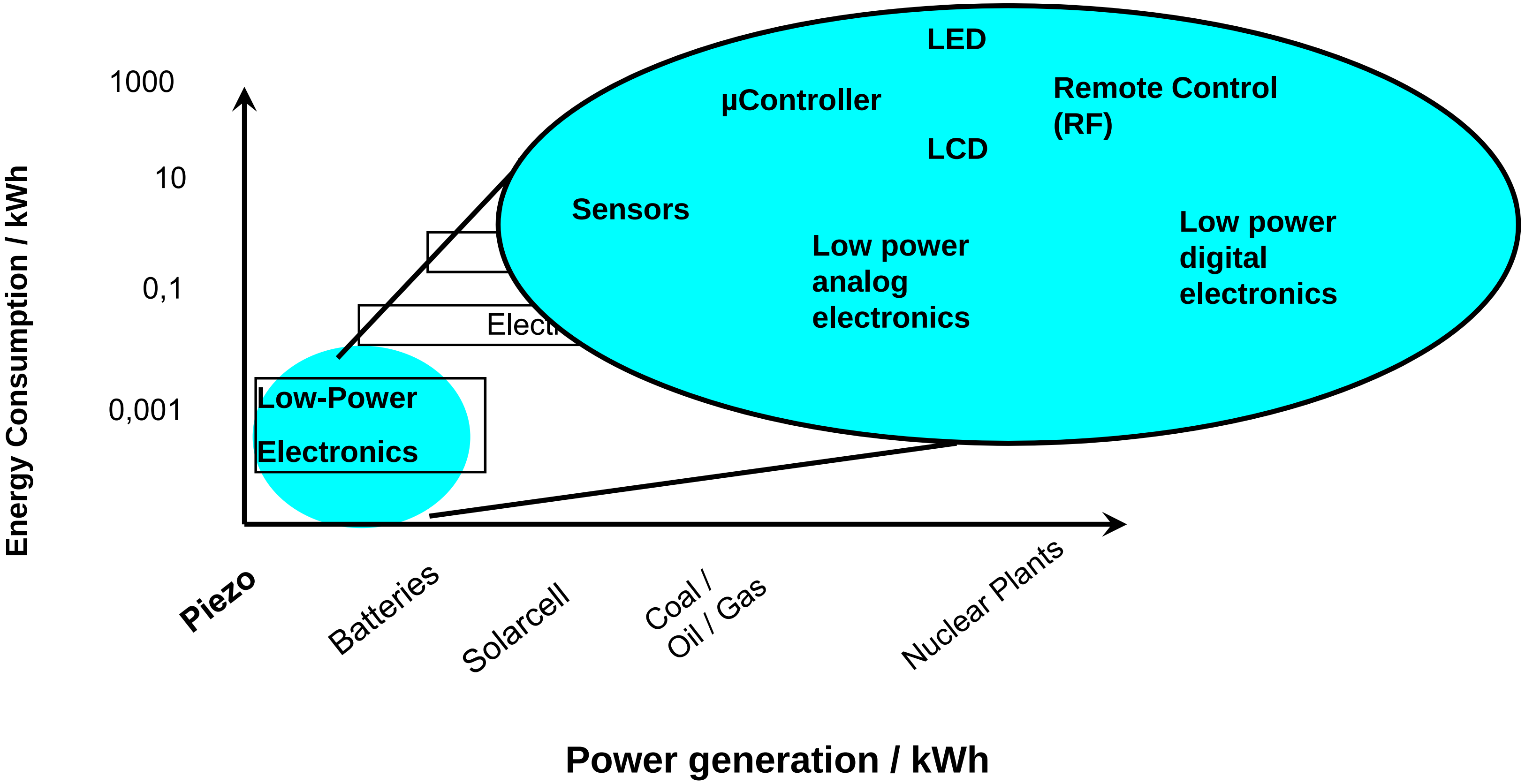
In plate-like structures (where material thickness is comparable to the ultrasound wavelength) it is possible to propagate guided waves (Lamb waves) parallel to the plate surfaces.

Lamb waves can propagate for considerable distances in plates thus making it possible to detect flaws over a sizable area with a single transducer (or pair of transducers).

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

Thomas Daue, Jan Kunzmann
Smart Material Corp.

Piezo ceramic energy harvesting = LOW POWER

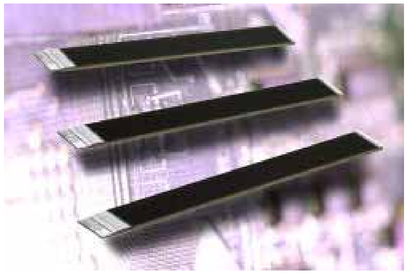


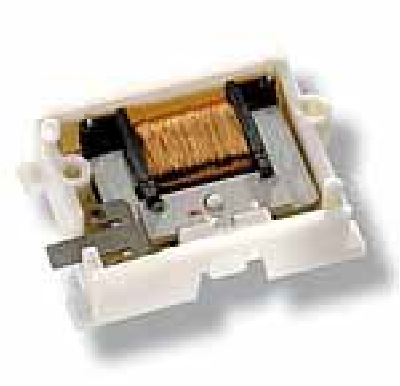
Cost feasibility checklist as of 2012

- Applications requiring < 3 mWs
- Long life time required, typical > 5 years
- Must work at high temperature changes -20C to 100C
- Present deflection > 50 µstrain to 1500 µstrain
- Applications with difficult access or high costs to change batteries
- Fully sealed systems
- Typically Efficacy of state-of-the art systems about 1.5 - 4% vibration to usable electric supply!
- *There are always exceptions!!!*

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

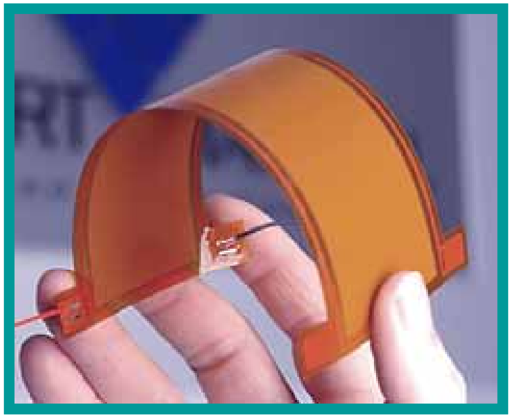




Photos courtesy Morgan Electro, EnOcean

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



iF
design award
2005

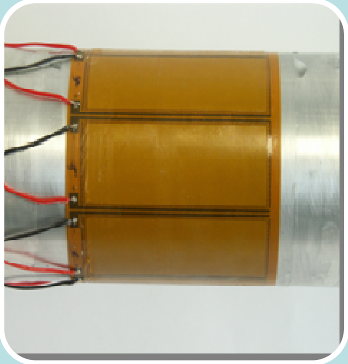
ALPAs overcome many problems - but not all

- 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

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
  - weight
  - no mechanical moving parts, can be made fully solid state

Low Frequency Application for ALPAs

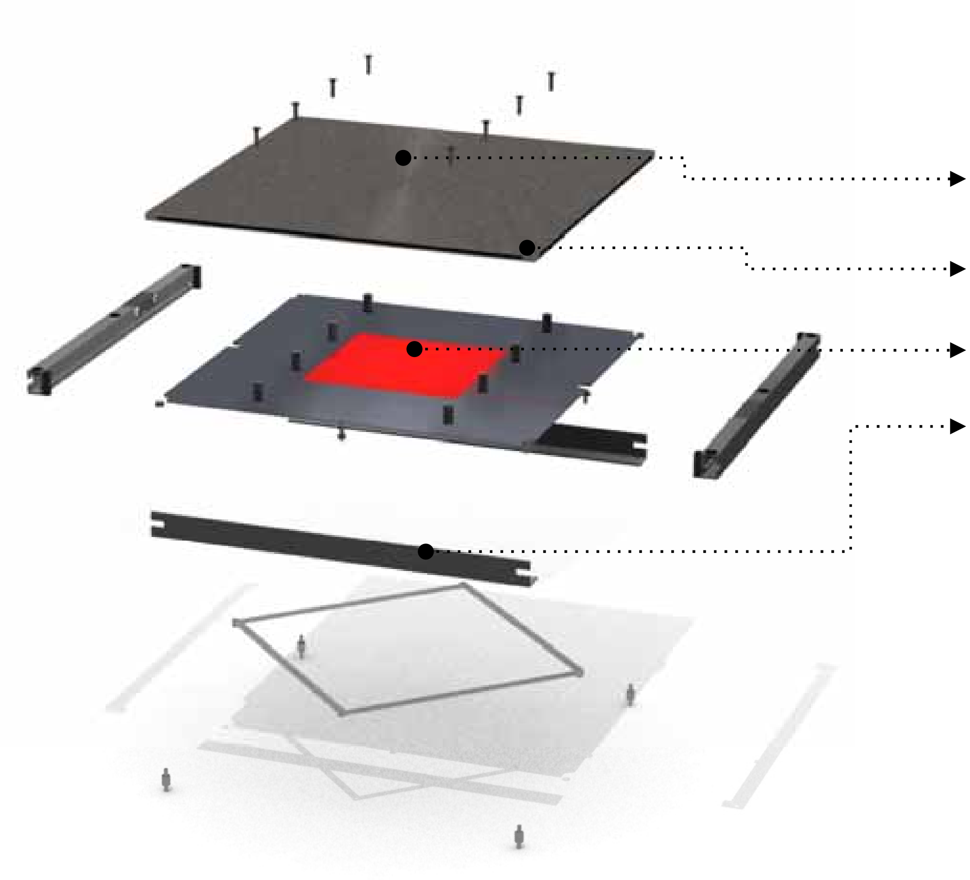
- Insole for shoes
  - requiring small profile
  - encapsulation, waterproof
  - long lifetime

- Chest band/Shirt

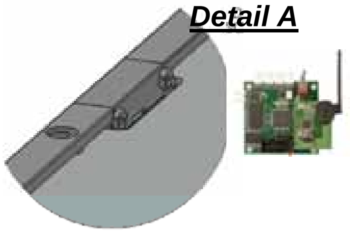
  - translating breathing motions

    in bending of a structure for harvesting

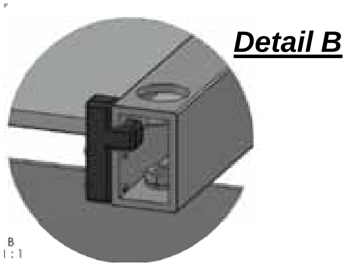
Smart Tile from POWERleap



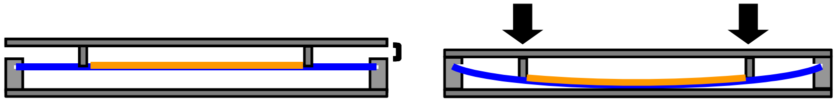
- Rigid Surface
- Foam Sealing Joints
- Bending Piezoelectric Shim
- Rugged Frame



Detail A

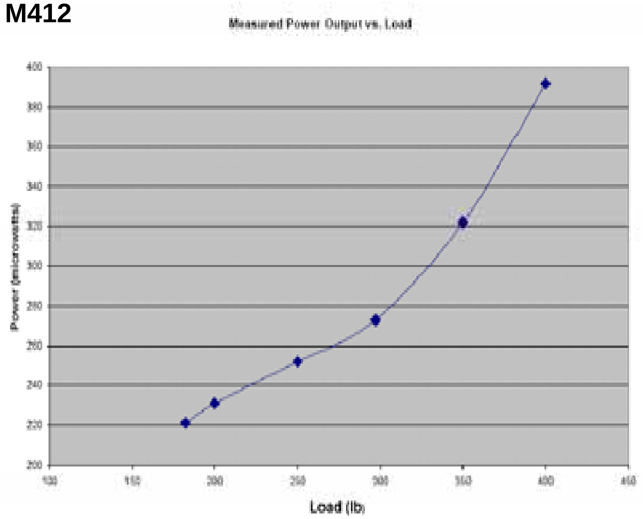


Detail B



Energy Harvesting Applications

Bell M412



Energy Harvesting on helicopter pitch links
(potos & data courtesy mircostrain inc., St. Arms)

Sikorsky H-60 Blackhawk

RF antenna

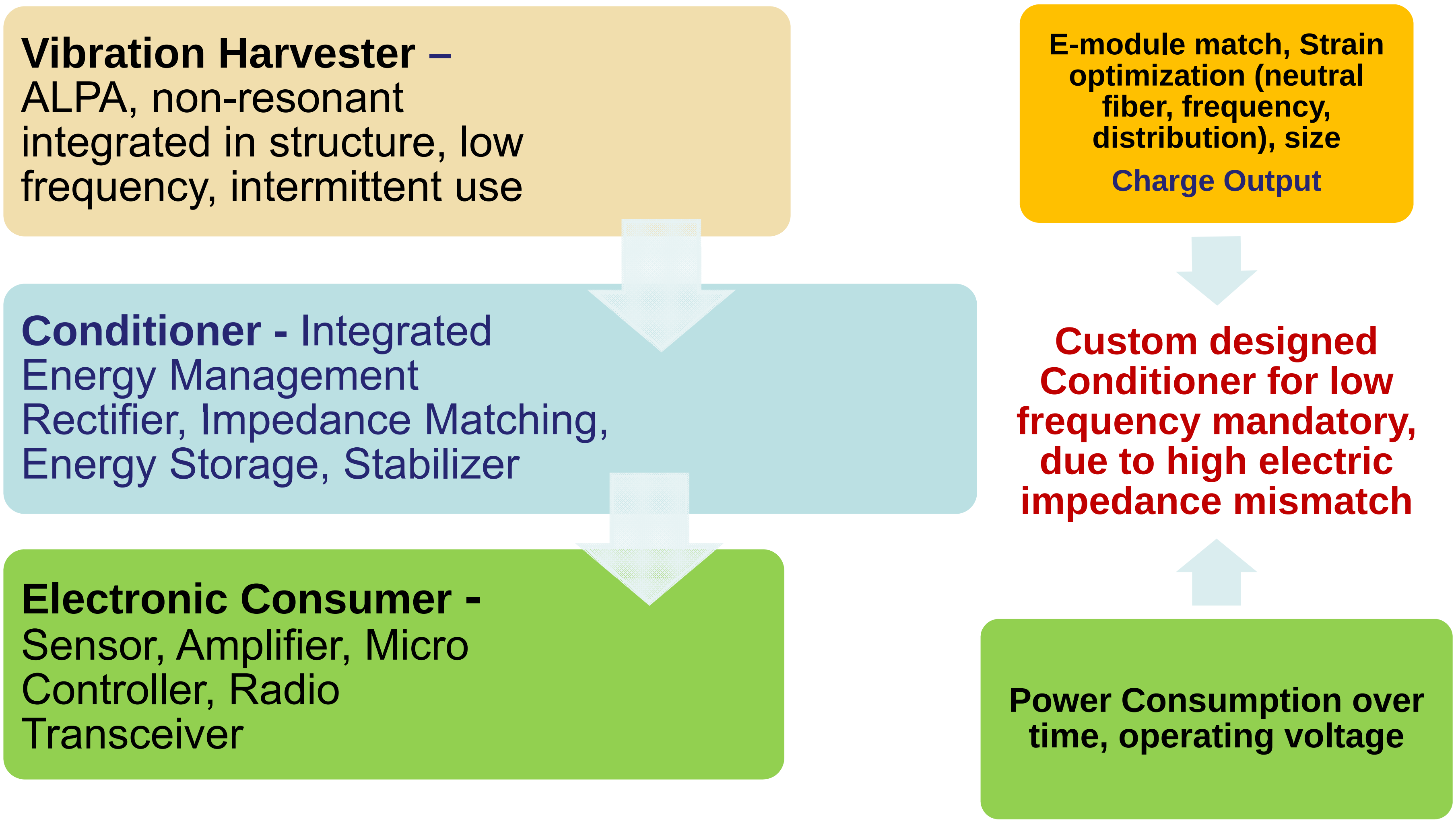
Circuit board module, microprocessor, and electrochemical battery

Piezoresistive strain gauge

Electrical insulation, EMI shielding, & protective covering (shown transparent for illustration purposes)

Piezoelectric energyharvesting elements

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

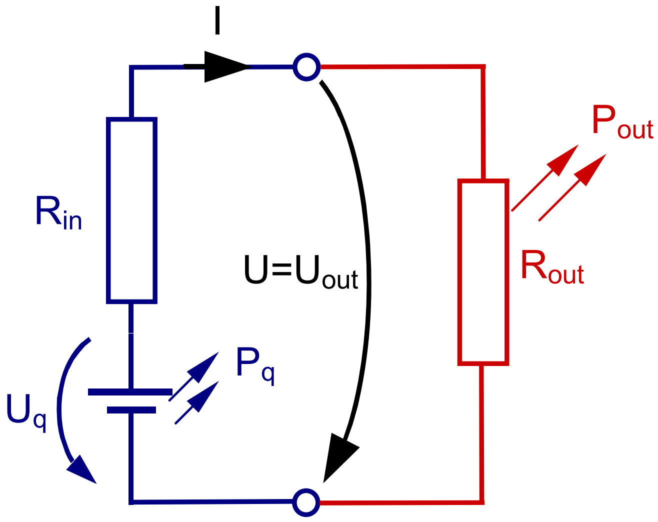
Power Consumption over time, operating voltage

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 often a charge coupled design for most cost effective and small size conditioner
- In a clamped setup, 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

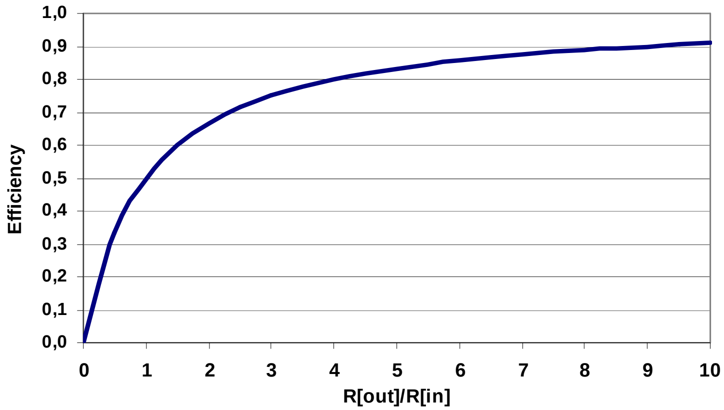
Basics of power transfer in active dipoles - Compromise



Efficiency

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

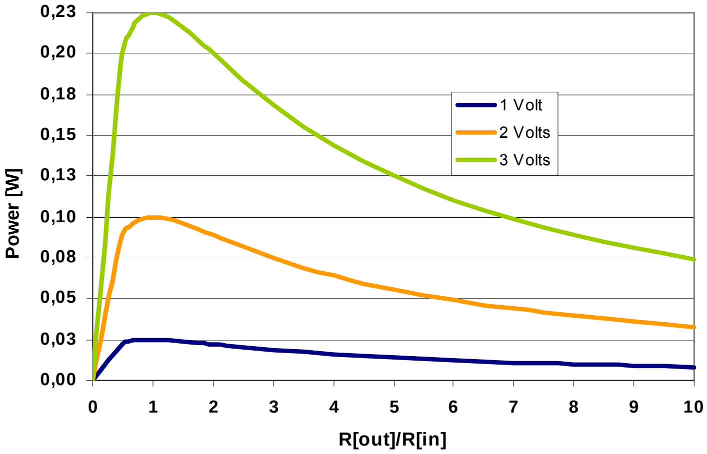
$R_{out} >> R_{in}$



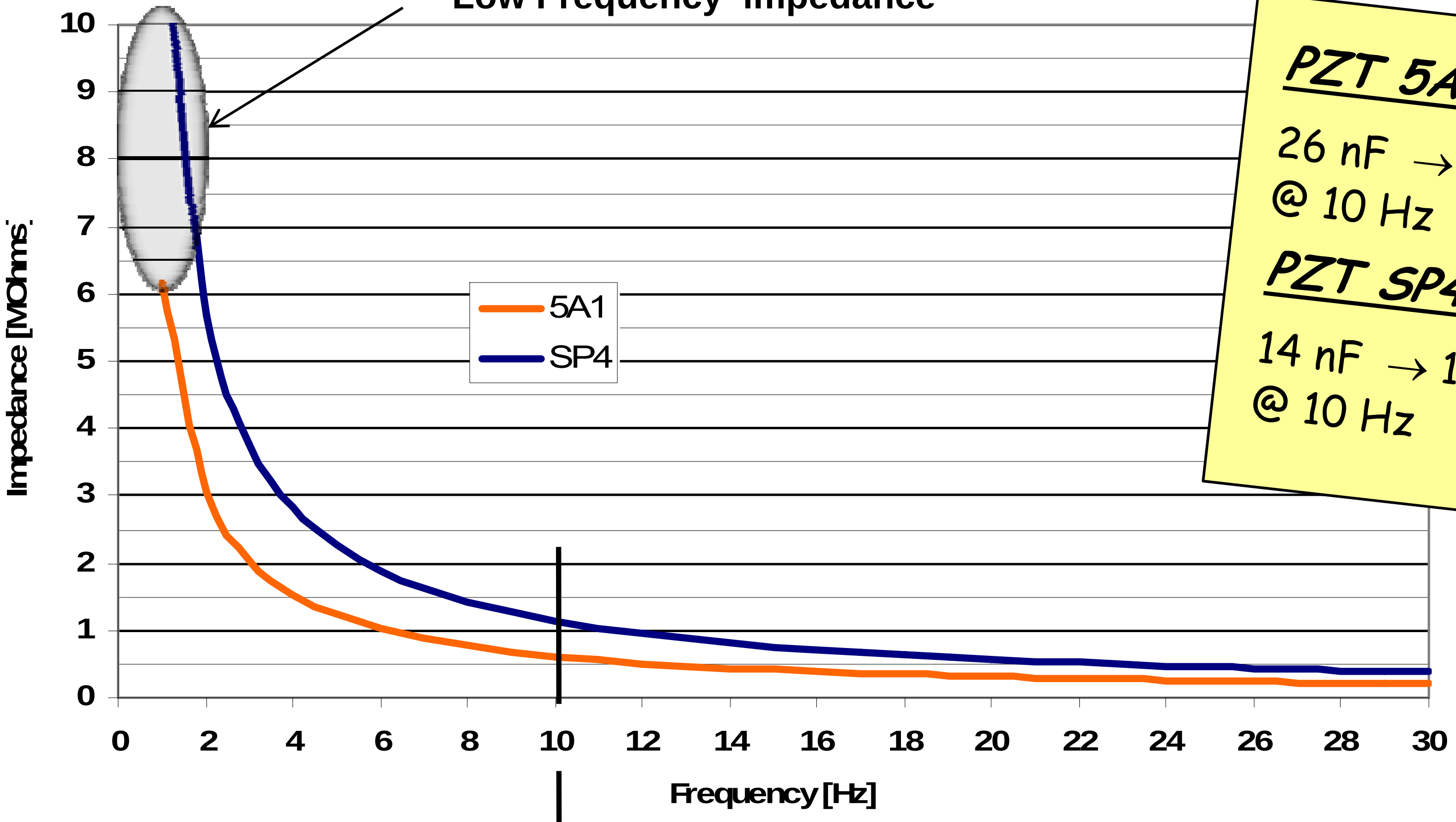
Energy Transfer

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

$R_{out} = R_{in}$



Dynamic impedance behavior for MFC M2814P2



Low Frequency impedance

10 Hz impedance value

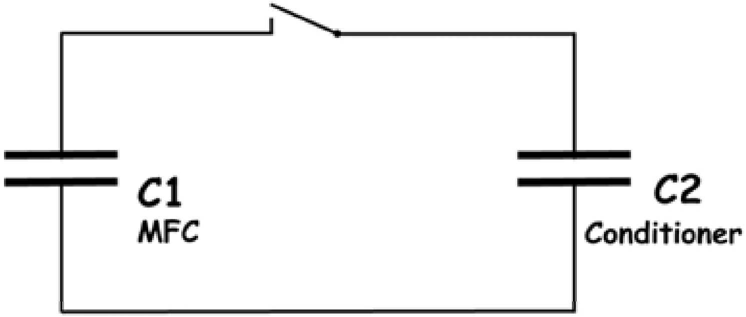
PZT 5A1:

26 nF → 600 kΩ
@ 10 Hz

PZT SP4:

14 nF → 1.1 MΩ
@ 10 Hz

Cap to Cap Energy Transfer Loss Problem



With **$Q = CU$** and **$E = ½\,C{*}U^2 \Rightarrow$**

$U_{C1+C2} = ½\,U_{C1}$

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

25% is maximum energy extraction!

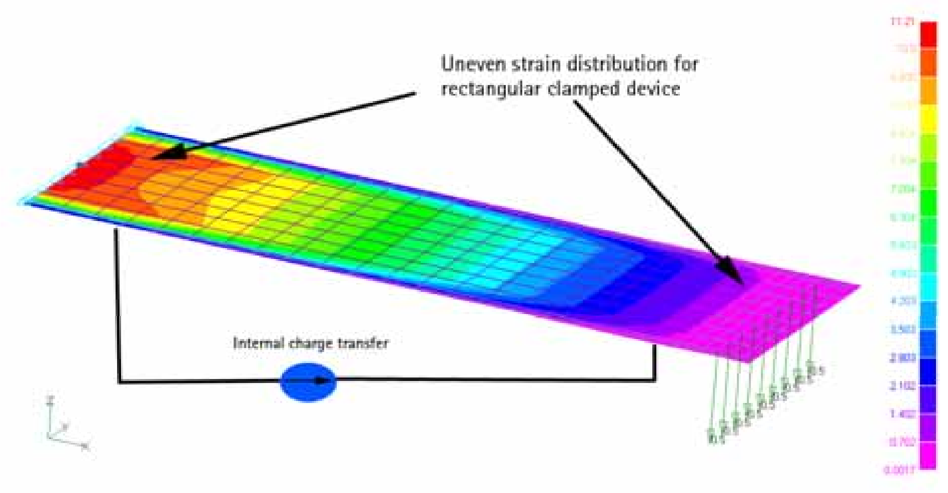
C1 = C2 optimum energy transfer

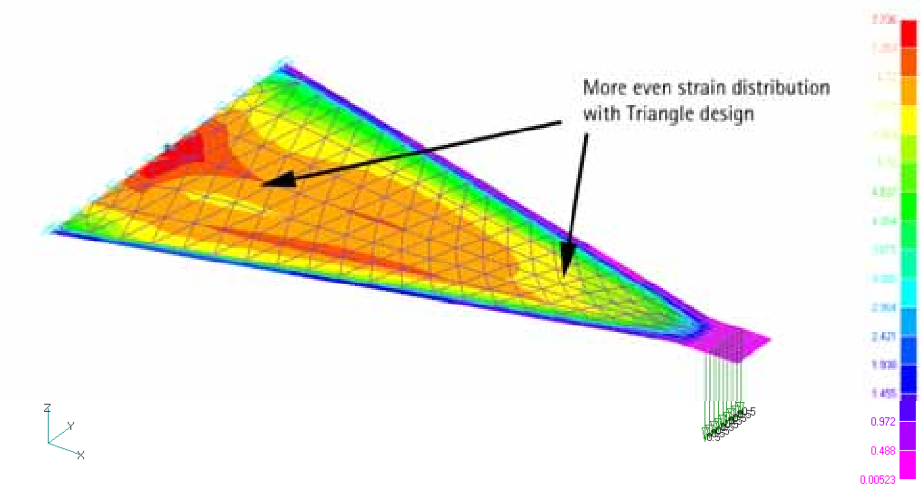
Voltage	20	**V**
C1	170	**nF**

8528-P2

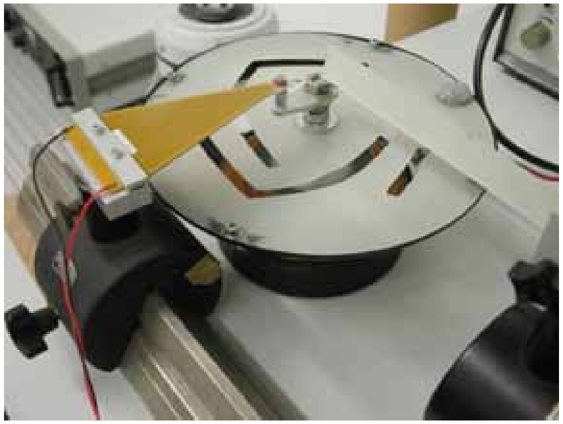
C1-C2 ratio		**0.01**	**0.02**	**0.05**	**0.1**	**0.2**	**1**	**2**	**5**	**10**	**20**	**50**	**100**
C2	**nF**	**1.7**	**3.4**	**8.5**	**17**	**34**	**170**	**340**	**850**	**1700**	**3400**	**8500**	**17000**
Initial charge in C1	As	3.4E-06	3.4E-06	3.4E-06	3.4E-06	3.4E-06	3.4E-06	3.4E-06	3.4E-06	3.4E-06	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

Charge transfer in clamped device – shape counts



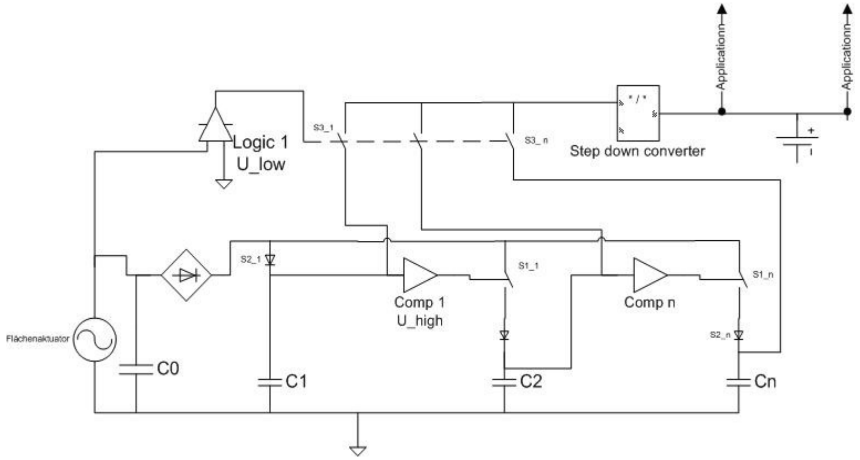


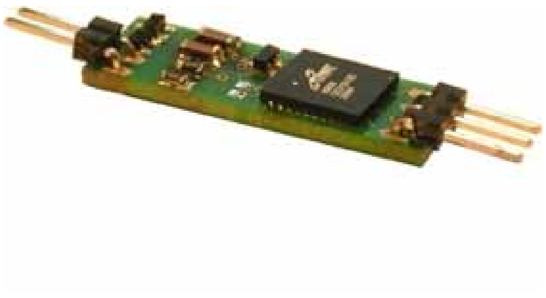
- Rectangular mechanically clamped PZT harvester result in uneven strain distribution over length
- this might cause device internal charge transfer between different areas of strain and lower the overall charge extraction
- triangle shaped PZT harvester are improving the strain distribution and overall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



Low Frequency Conditioner EH-CL50

- Standard Energy Harvesting Conditioners, now available as chipsets or standard circuit DO NOT imply good performance for low frequency/intermittent piezo ceramic 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





Patent pending

SYMPOSIUM & EXHIBITION

ISPA 2013

INTERNATIONAL SYMPOSIUM ON PIEZOCOMPOSITE APPLICATIONS

September 19-20, 2013

Fraunhofer Institute Center
Dresden, Germany

Topics

- Intelligent light-weight design
- Reduced energy consumption
- Performance, increased safety
- Progress in series production
- Industrial applications

Thank you for your attention