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.
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

Polarisations achse

- **a)**
- **b)**
- **c)**

- **d)**
- **e)**
- **f)**

**direct Piezo-Effect**

**inverse 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)
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

AFC
Active Fiber Composite

MFC
MacroFiber Composite

SFC

RFD
Radial Field Diaphragm

Quickpak
Clemson Univ. SC, USA
RAINBOW

M.I.T.
NASA

Fraunhofer

NASA

DLR

Funktions-
Modul

1990
1995
2000
2005
2009
MFC – Principals of operation

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

<table>
<thead>
<tr>
<th>Device</th>
<th>Operation voltage</th>
<th>Capacity</th>
<th>Sensor characteristic</th>
<th>Actuator characteristic</th>
<th>Generator characteristic</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>$V_{op}^+ [V]$</td>
<td>$V_{op}^- [V]$</td>
<td>$C_{pol} [nF/cm^2]$</td>
<td>$d_{33}^{eff} [pC/N]$</td>
<td>$d_{31}^{eff} [pC/N]$</td>
</tr>
<tr>
<td>3-3 MFC</td>
<td>1500</td>
<td>-500</td>
<td>0.42</td>
<td>460</td>
<td>-</td>
</tr>
<tr>
<td>3-1 MFC</td>
<td>360</td>
<td>-60</td>
<td>4.5</td>
<td>-</td>
<td>-370</td>
</tr>
</tbody>
</table>
**Basics for calculation**

**Work diagram**

- **Weg** (Weg)
- **Leerlaufhub**
- **Arbeitspunkte**
- **Blockierkraft**
- **Kraft**

**Optimal substrate thickness for max energy transfer**

- **Aluminium**
- **Steel**
- **Carbon Fiber**

---

**Electrical Properties:**

| High-field (\(|E| > 1\text{kV/mm}\)), biased-voltage-operation piezoelectric constants: |  |
|---|---|
| \(d_{33}^{**}\), P1 type | \(4.6 \times 10^2 \text{pC/N}\) |
| \(d_{33}^{**}\), P2 type | \(-3.7 \times 10^2 \text{pC/N}\) |
| Free-strain* per volt P1 type | \(-0.75 - 0.9 \text{ppm/V}\) |
| Free-strain* per volt P2 type | \(-2 \text{ppm/V}\) |
| Generator characteristics P1 type | \(-1650 \text{pC/ppm}\) |
| Generator characteristics P2 type | \(-3650 \text{pC/ppm}\) |
| Free-strain hysteresis* | \(-0.2\) |

**Orthotropic Linear Elastic Properties (constant electric field):**

- Tensile modulus, \(E_1^{**}\): 30.34 \text{GPa}
- Tensile modulus, \(E_2^{**}\): 15.86 \text{GPa}
- Poisson's ratio, \(\nu_{12}\): 0.31
- Poisson's ratio, \(\nu_{21}\): 0.16
- Shear modulus, \(G_{12}^{**}\): 5.52 \text{GPa}

**Operational Parameters:**

- Maximum operational positive voltage, \(V_{\text{max}}\): +1500 \text{V P1 type, 3600 V P2 type}
- Maximum operational negative voltage, \(V_{\text{min}}\): -500 \text{V P1 type, -50V P2 type}
- Linear-elastic tensile strain limit: 1000 ppm
- Maximum operational tensile strain: \(~4500 \text{ppm}\)
- Peak work-energy density: \(~1000 \text{in-lb/in}^2\)
- Maximum operating temperature: \(<140^\circ \text{C or 284^\circ F}\)
- Operational lifetime (@ 1kV-p): \(>10 \times 10^9\) cycles
- Operational lifetime (@ 2kV-p, 500VDC): \(>10 \times 10^7\) cycles
- Operational bandwidth: \(<10 \text{kHz}\)
Überblick

Anwendungen

Actuators

Sensors

Energy Harvesting
Space & Aircraft Applications

Active Twist Rotor (NASA, ARL, University of Michigan, Sikorsky)
Space & Aircraft Applications

Twin-tail buffet loads alleviation (NASA, AFRL, Boeing)
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
Deicing System for the Predator Drone

Photos courtesy GA-ASI, Patents Pending
Fully solid state flight control for small UAVs

- UAVs up to 2m wing span, elevators and ailerons controlled with MFCs.
- Allows to fold the wings around fuselage for compact transportation/deployment and adding business in flight operations.
- Developed by System Dynamics under US Army contract.
- New generation of power supplies developed with AMPower, USA. Low cost, battery operated device for -500 to 1500V output for the MFC.

Cascading Bimorph Variable-Camber Airfoil with Internal Compliant Hinge in Wind Tunnel Actuated with MFCs
Virginia Tech, July 2008, (c) Onur Bilgen

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

- 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.

Photos courtesy SWAC

SmartCharge™
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
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
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

Operational modes
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

POWERleap Inc. | 2011 © All rights reserved
Energy Harvesting Applications

Sikorsky H-60 Blackhawk

Bell M412

RF antenna
Circuit board module, microprocessor, and electrochemical battery
Piezoresistive strain gauge
Electrical insulation, EMI shielding, & protective covering (shown transparent for illustration purposes)
Piezoelectric energy harvesting elements

Energy Harvesting on helicopter pitch links (photos & data courtesy microstrain inc., St. Arms)
Vibration Harvester – Typical Design & Challenge

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


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

\[ P_{out} = U_{q}^2 \cdot \frac{R_{out}}{(R_{in} + R_{out})^2} \]

\[ R_{out} = R_{in} \]
Dynamic impedance behavior for MFC M2814P2

**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 \( E = \frac{1}{2} C*U^2 \) =>
\[ U_{C1+C2} = \frac{1}{2} U_{C1} \]

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

25% is maximum energy extraction!
C1 = C2 optimum energy transfer

<table>
<thead>
<tr>
<th>Voltage</th>
<th>20 V</th>
</tr>
</thead>
<tbody>
<tr>
<td>C1</td>
<td>170 nF</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>C1-C2 ratio</th>
<th>0.01</th>
<th>0.02</th>
<th>0.05</th>
<th>0.1</th>
<th>0.2</th>
<th>1</th>
<th>2</th>
<th>5</th>
<th>10</th>
<th>20</th>
<th>50</th>
<th>100</th>
</tr>
</thead>
<tbody>
<tr>
<td>C2</td>
<td>nF</td>
<td>1.7</td>
<td>3.4</td>
<td>8.5</td>
<td>17</td>
<td>34</td>
<td>170</td>
<td>340</td>
<td>850</td>
<td>1700</td>
<td>3400</td>
<td>8500</td>
</tr>
<tr>
<td>Initial charge in C1</td>
<td>As</td>
<td>3.4E-06</td>
<td>3.4E-06</td>
<td>3.4E-06</td>
<td>3.4E-06</td>
<td>3.4E-06</td>
<td>3.4E-06</td>
<td>3.4E-06</td>
<td>3.4E-06</td>
<td>3.4E-06</td>
<td>3.4E-06</td>
<td>3.4E-06</td>
</tr>
<tr>
<td>Initial energy in C1</td>
<td>mWs</td>
<td>0.034</td>
<td>0.034</td>
<td>0.034</td>
<td>0.034</td>
<td>0.034</td>
<td>0.034</td>
<td>0.034</td>
<td>0.034</td>
<td>0.034</td>
<td>0.034</td>
<td>0.034</td>
</tr>
<tr>
<td>Voltage after switching</td>
<td>V</td>
<td>19.80</td>
<td>19.61</td>
<td>19.05</td>
<td>18.18</td>
<td>16.67</td>
<td>10.00</td>
<td>6.67</td>
<td>3.33</td>
<td>1.82</td>
<td>0.95</td>
<td>0.39</td>
</tr>
<tr>
<td>Charge in C2</td>
<td>As</td>
<td>3.4E-07</td>
<td>6.7E-08</td>
<td>1.6E-07</td>
<td>3.1E-07</td>
<td>5.7E-07</td>
<td>1.7E-06</td>
<td>2.3E-06</td>
<td>2.8E-06</td>
<td>3.1E-06</td>
<td>3.2E-06</td>
<td>3.3E-06</td>
</tr>
<tr>
<td>Energy in C2</td>
<td>mWs</td>
<td>0.00033</td>
<td>0.00065</td>
<td>0.00154</td>
<td>0.00281</td>
<td>0.00472</td>
<td>0.0085</td>
<td>0.00756</td>
<td>0.00472</td>
<td>0.00281</td>
<td>0.00154</td>
<td>0.00065</td>
</tr>
<tr>
<td>Energy C2 % of initial</td>
<td>%</td>
<td>1.0</td>
<td>1.9</td>
<td>4.5</td>
<td>8.3</td>
<td>13.9</td>
<td>25.0</td>
<td>22.2</td>
<td>13.9</td>
<td>8.3</td>
<td>4.5</td>
<td>1.9</td>
</tr>
<tr>
<td>Energy in C1 after switch</td>
<td>mWs</td>
<td>0.03333</td>
<td>0.03268</td>
<td>0.03084</td>
<td>0.0281</td>
<td>0.02361</td>
<td>0.0085</td>
<td>0.00378</td>
<td>0.00094</td>
<td>0.00028</td>
<td>7.7E-05</td>
<td>1.3E-05</td>
</tr>
<tr>
<td>Total Energy after switch</td>
<td>mWs</td>
<td>0.0337</td>
<td>0.0333</td>
<td>0.0324</td>
<td>0.0309</td>
<td>0.0283</td>
<td>0.0170</td>
<td>0.0113</td>
<td>0.0057</td>
<td>0.0031</td>
<td>0.0016</td>
<td>0.0007</td>
</tr>
</tbody>
</table>
| 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
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

www.ikts.fraunhofer.de
Thank you for your attention