Macro Fiber Composite

as

low cost strain and vibration sensor

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Macro fiber composite as a low cost strain and vibration sensor

Overview

- Strain Sensor Elements - Macro Fiber Composites
  - Structural design
  - Types, Materials and Properties

- Motivation

- Suitable electronics
  - Voltage Amplifier vs. Charge Amplifier
  - Store&Hold Amplifier

- Applications
  - Static / low frequency
  - Vibration / Sound
  - Ultrasound

- Summary & Conclusions

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Strain Sensor Elements - Macro Fiber Composites (MFC)

Disadvantages of solid plate actuators

- nonelastic, no surface conformity
- only use of $d_{31}$ in-plane
- Isotropic in-plane deflection
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## Strain Sensor Elements - available MFC Types

<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/cm²]</td>
<td>$d_{33}^{\text{eff}}$ [pC/N]</td>
<td>$d_{31}^{\text{eff}}$ [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>

**P1-Type MFC (d33)**
- **Elongator**

**P2-Type MFC (d31)**
- **Contractor**
Motivation

- cantilever beam set-up
- +/- 3 mm tip deflection (controlled)
- 1 Hz / 5 Hz / 10 Hz
- 1 MΩ input impedance (oscilloscope)

Piezo-equivalent model

Outer load leads to a continuous discharging of the sensor’s capacitance
Special high impedance (load free) electronics are needed for quantitative measurements
State of the Art - **Voltage amplifier vs. Charge amplifier**

- $R_e, C_e$ ... MFC- and wire-specific parameters
- $R_g, C_g$ ... Parameters in the feedback circuit
- $Q_0 = d F_0$ ... Charge at $t = t_0$

\[
\begin{align*}
  u_1 & \sim \frac{Q_0}{C_e} e^{-\frac{t}{R_e C_e}} \\
  u_2 & = \frac{Q_0}{C_g} e^{-\frac{t}{R_g C_g}}
\end{align*}
\]

$u_1 = f$ (MFC material and wiring cables)  
$u_2 = f$ ($R_g$ and $C_g$ in the feedback circuit)
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State of the Art - *Voltage amplifier vs. Charge amplifier*

**Force at MFC:**
\[ t = t_0, \ F = F_0 \]
\[ t = t_1, \ F = F_1 \ldots \]

**Output at voltage amplifier:**
\[ u_1 \]
time-variant \((R_e, C_e)\)
for dynamic measurements

**Output at charge amplifier:**
\[ u_2 \]
time-invariant \((R_g \to \infty)\)
for static measurements

Drift (noise integration) is critical

Not applicable for static measurements
"New" approach – Store&Hold Amplifier

Principle often used in analog synthesizer keyboard units based on the earlier developments by Robert Arthur Moog in 1950.

Generated charge is stored in a nearly leakage free capacitor and held there for a longer time by measuring the voltage load free with a high impedance voltage follower.
Fields of Applications

- **static / low frequency**
  - deformation
  - pressure
- **vibrations / sound**
  - mechanical vibrations
  - body sound propagation
- **ultrasound**
  - acoustic emission
  - guided wave ultrasound

- **strain based applications**
  - store&hold amplifier
  - voltage amplifier
  - store&hold amplifier
  - voltage amplifier
Applications – *quasi-static strain measurements*

\[
\varepsilon = \frac{\sigma}{E} = \frac{M_b}{W_b} = \frac{6 \, F \, a}{b \, h^2 \, E}
\]

- **E-Modul**: 210.000 N mm\(^{-2}\)
- **length a**: 121 mm
- **bar height h**: 6 mm
- **bar width b**: 20 mm
- **force F**: 15 N
Applications – *quasi-static strain measurements*

- Strain gauge
- MFC (M-2807)

Storage capacitance not optimized, capacitors: $C_e / C_g \approx 0.0015$

Storage capacitance optimized, capacitors: $C_e / C_g \approx 0.56$

*Applications – quasi-static strain measurements*
Applications – *low frequency pressure sensor*

\[ p = \frac{F_0}{A} = \frac{Q_0}{d_{33} A} \rightarrow Q_0 = p \cdot d_{33} \cdot A \]

\( d \) … piezoelectric charge coefficient
Applications – low frequency pressure sensor

various storage capacitances
(pressure 2,5 bar=const.)

various pressure levels
(capacitance 22nF=const.)

- cap. ≈ 0,2 nF
- cap. ≈ 2,2 nF
- cap. ≈ 22 nF

- press. ≈ 6,0 bar
- press. ≈ 2,5 bar
- press. ≈ 1,0 bar

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Applications – *vibration sensor for flow meters*

**Principle of work**

Most of the monolithic ceramic sensors break after a short life time.

Stress analysis shows high values for stresses and their gradients.

**Sensor Pin**

**FEA model**

**FEA results** ($\sigma_{\text{max}} = 400 \text{ N/mm}^2$)
Applications – vibration sensor for flow meters

MFC based sensor development

FEA results (\(\sigma_{\text{max}}=-100 \text{ N/mm}^2\))

Prototyping

Results:

- Max stresses could be reduced down to a fourth and are compressive only
- Sensitivity of the novel sensor element is closely comparable to the original sensor element
Applications – *sound pick-up system for acoustic instruments*

The *ideal sound* is religion for the most of musicians.

Therefore position and frequency response of the pick-up are a question of individual taste.
Applications – *sound pick-up system for acoustic instruments*

**Results:**
- Neck and bridge position give an equalized response
- P1 type MFCs have a better high frequency transparency
- An-isotropic behavior gives a higher DOF for positioning
- MFCs measure strain proportional
- Acceleration sensors measure acceleration proportional
Applications – *ultrasound structural health monitoring*

Currently up-growing research activities on the field of ultrasound guided wave inspection systems.

**Principle:**

- Cracks
- Corrosion (inside)
- Corrosion (outside)

Advantages using MFC‘s :

- Flexible design allows wrap around
- $d_{33}$ effect offers excellent acoustic performance and sensitivity
- Basics of MFC technology open a wide range for cost effective layouts along specific acoustic requirements

*Fields of application*:

- Pipeline inspection
- Antenna or wind mill masts
- Quality control for metal coils and ropes
- Monitoring of thin and straight structures (wind turbine blades)
Applications – \textit{ultrasound structural health monitoring}

\textit{Smart PowerSonic}™
+/-280V up to 100 kHz

10 cycle 30 kHz burst

Reverberations from both ends

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Summary & Conclusions

Based on their unique design the MFC elements combine most of the basic requirements for strain sensors like high sensitivity, robustness, reliability and an anisotropic behavior.

Voltage and charge amplifiers as commercially available equipment match the specific electric behavior of piezo sensors well, but they are also showing some essential drawbacks like signal stability and drift.

With the Store&Hold amplifier a novel electronic unit was developed and evaluated to overcome the disadvantages of current systems.

Based on several applications it was shown that MFC sensors combined with modified electronics offer an incredible variety of new and interesting applications.

Those results motivated us to force the future the work on both the MFC sensor and the pre-amplifier as well. We plan to comercialize that system next time under the name SmartCharge™.
Thank you for your attention

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