Modellierung, Entwurf und automatisierte Herstellung von Multilayer-Polymeraktoren

Modeling, design and automated fabrication of polymer-based multilayer actuators

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Outline

1. Introduction

2. Modelling of DEAP-based multilayer actuators

3. DEAP stack-actuator design

4. Automated manufacturing process

5. Conclusion
1. Electroactive Polymers – Introduction

Considered will be electronic EAPs and in particular dielectric electroactive polymer transducers denoted as DEAP transducers.

- Fundamental design of a DEAP transducer

- Functional principle is based on the electrostatic pressure that results when the DEAP is charged:

\[
\sigma_{el} = \varepsilon_0 \cdot \varepsilon_r \cdot E^2 = \varepsilon_0 \cdot \varepsilon_r \cdot \left(\frac{v_p}{t}\right)^2
\]

\(v_p = 0\) V \(\neq 0\) V
1. Properties of DEAP-based transducers

- Polymer acts as a dielectric
  - capacitance $C_p$
- Parasitics of polymer and electrode
  - loss resistances $R_p$ and $R_e$

- Electrical Parameters depend on the mechanical state
  - Due to the **electromechanical coupling** DEAP transducer can be used as actuators, sensors and generators

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Electrical Energy

Mechanical Energy

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Modeling, design and fabrication of DEAP actuators
1. DEAPs as sensors and generators

DEAP as sensor
- Electrical parameters depend on mechanical state $\lambda$
- Identification of at least one electrical parameter

Sensor-based concepts
DEAP exclusively used as sensor

Sensor-less concepts
DEAP transducer is simultaneously used as sensor

DEAP as (electrostatic) generator

- Initial system
- Discharge DEG
- Charge DEG
- Maximum field strength
- Relax DEG
- Minimum strain
- Stretch DEG
- Maximum strain
1. DEAP Multilayer Actuators for pulling and pushing

Actuation in direction of the electric field

- **Compression** of the polymer in z-direction
- **Pulling force** in z-direction

Actuation perpendicular to the electric field

- **Elongation** of the polymer in z-direction
- **Pushing force** in z-direction

**DEAP stack-actuator**

Multilayer $\Rightarrow$ increasing the absolute deformation $\Delta l$

$\Delta l \Rightarrow \lambda_z < 1$

$V_{DE} \neq 0 V$

**DEAP roll-actuator**

Multilayer $\Rightarrow$ increasing the pushing force

$\Delta l \Rightarrow \lambda_z > 1$

$v_{DE} \neq 0 V$

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Modeling, design and fabrication of DEAP actuators
1. Applications of DEAP multilayer actuators

- DEAP actuators are predestined for position applications in small devices
- Promising technology e.g. for automation applications, haptic feedback...

DEAP actuators are predestined for position applications in small devices and are promising technology, particularly for automation applications such as haptic feedback.

- pneumatic valves & gripper

- electrical contactors

- force feedback glove
1. DEAP Roll-actuator with polymer core

- New roll-actuator design
- Bi-axially prestretched active material is winded up around compressed polymer core.
- Prestretched polymer core must support the force in the operating point of the actuator caused by the prestretched DEAP material.

1. DEAP Roll-actuator with polymer core

No-load-strain behavior of the realized prototype:

Parameters of the prototype:

\[ l_0 = 31\,\text{mm}; \quad t_0 = 40\,\mu\text{m}; \quad N = 20; \quad r_{o,N,0} = 5\,\text{mm} \]

\[ \lambda_{z,EAP} = 1.07; \quad \lambda_{y,EAP} = 1.2; \quad Y_{EAP} = 4.5\,\text{MPa}; \quad Y_{core} = 1\,\text{MPa} \]
2. Modelling of DEAP-based multilayer actuators

- Stack-actuator: actuator films are
  - mechanically connected in series
  - electrically connected in parallel

One actuator film describes the stretch-force-behavior of the whole actuator

Electrode

Polymer

\[ t = \lambda_z \cdot t_0 \]

Electromechanical coupling:
\[ \sigma_{el} = \varepsilon_0 \cdot \varepsilon_r \cdot E^2 \]

Yield strength:
\[ Y = 3\text{MPa}; \varepsilon_r = 7; \]
\[ A_0 = 64\text{mm}^2 \]

Current limit under consideration of the lifetime

\[ F_{act} = A \left[ \sigma_{el} - \sigma_{elast} \right] = \frac{A_0}{\lambda_z} \cdot \left[ \varepsilon_0 \cdot \varepsilon_r \cdot \frac{E_0^2}{\lambda_z^2} + \frac{Y}{3} \left( \lambda_z^2 - 1 \right) \right] \]

Hyperelastic material behavior:
\[ \sigma_i = \lambda_i \cdot \frac{\partial W}{\partial \lambda_i} - p \]

Using Neo-Hookean approach, equibiaxial deformation in x- and y-direction

2. Stretch-force-behavior of a DEAP stack-actuator

- Optimizing the actuator based on a dimensionless, normalized stretch-force-behavior
  
  - energy density $u_c$ stored in the (constant) DEAP capacitance:

  $$u_c = \frac{U_c}{V} = \frac{C_p \cdot V_p^2}{2 \cdot V} = \frac{1}{2} \cdot \varepsilon_0 \cdot \varepsilon_r \cdot E^2 = \frac{\sigma_{el}}{2}$$

  - substitution of the electrostatic pressure:

  $$F_{act} = \frac{A_0}{\lambda_z} \cdot \left[ 2 \cdot u_c + \frac{Y}{3} \cdot \left( \lambda_z^2 - \frac{1}{\lambda_z} \right) \right]$$

  - normalizing the force and the energy density a dimensionless charateristic results:

  $$\frac{F_{act}}{A_0 \cdot Y} = \frac{1}{\lambda_z} \cdot \left[ \frac{2 \cdot u_c}{Y} + \frac{1}{3} \cdot \left( \lambda_z^2 - \frac{1}{\lambda_z} \right) \right]$$

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2. Stretch-force-behavior of a DEAP stack-actuator

- Operation with constant energy density equals operation with constant electric field

\[
\frac{u_c}{Y} = \text{const.} \quad \Rightarrow \quad E = \frac{v_p}{t} = \text{const.} \quad \Rightarrow \quad v_p = E \cdot t_0 \cdot \lambda_z
\]
2. Design Optimization

- Stretch-force-behavior has two characteristics
  - **Blocking-force** (obtained if the actuator cannot deform)
  - **No-load-stretch** (obtained if the actuator generates no force → free stroke)
2. Design Optimization – Blocking-Force

- Operating the actuator at a constant stretch $\lambda_{z,0}$ the resulting force is linearly increased with the electrical energy density:

$$\frac{F_{\text{act}}}{A_0 \cdot Y} = \frac{2}{\lambda_{z,0}} \cdot \frac{u_c}{Y} + \frac{1}{3} \left( \lambda_{z,0} - \frac{1}{\lambda_{z,0}^2} \right)$$

- If a pre-stretch (load) $\lambda_{z,0}$ is applied the blocking-force results to:

$$\frac{F_{\text{act}}}{A_0 \cdot Y} = \frac{2}{\lambda_{z,0}} \cdot \frac{u_c}{Y}$$

→ Blocking-Force is **scalable by cross-sectional area** $A_0$ but is **independent from the Young’s modulus** $Y$

→ Slope is adjustable by applied **pre-load** $\lambda_{z,0}$

Blocking-Force is scalable by cross-sectional area $A_0$ but is independent from the Young's modulus $Y$. Slope is adjustable by applied pre-load $\lambda_{z,0}$.
2. Design Optimization – No-Load-Stretch

- The no-load-stretch is obtained if no force is exerted:

\[ F_{act} = 0 \quad \Rightarrow \quad 2 \cdot u_c = \sigma_{elast} \]

\[ \lambda_z = (\beta) \frac{2 \cdot u_c}{Y} \cdot \frac{1}{\beta}, \]

with \( \beta = \sqrt[3]{\frac{8 \cdot u_c^3}{Y^3} + \frac{1}{4} + \frac{1}{2}} \)

- Using a linear-elastic approach a comparable equation results:

\[ \sigma_{elast} = \varepsilon_c \cdot Y = (\lambda_z - 1) \cdot Y = -2 \cdot u_c \]

\[ \lambda_z = 1 - \frac{2 \cdot u_c}{Y} \quad \Rightarrow \quad (\beta = 1) \]

- No-Load-Stretch is independent from the geometry but decreases with increasing Young’s modulus \( Y \):
2. Design Optimization – Coupling Coefficient

- **Optimization of mechanical work density** with respect to the applied electrical energy

  - Instantaneous mechanical work:
    \[
    w = \frac{W}{V} = \frac{F_{act} \cdot \Delta l}{V} = \frac{F_{act}}{A_0} \cdot (1 - \lambda_z)
    \]

  - This also yields to a normalized mechanical energy density:
    \[
    \frac{w}{Y} = \frac{1 - \lambda_z}{\lambda_z} \cdot \left[ 2 \cdot \frac{u_c}{Y} + 1 \cdot \left( \lambda_z^2 - \frac{1}{\lambda_z} \right) \right]
    \]

  - Operating point with maximum electromechanical coupling:
    \[
    \frac{d \ w}{d \lambda_z} = 2 - \lambda_z \cdot \left( 1 + 6 \frac{u_c}{Y} \right) + \lambda_z^3 - 2 \lambda_z^4 = 0 \quad \Rightarrow \quad \lambda_{z, opt}
    \]
2. Performance Limitations

- Operating the stack-actuator with a **constant voltage** a corresponding initial energy density results:
  \[
  \frac{V_{p,0}}{t_0} = \frac{V_p}{t} \cdot \lambda \Rightarrow u_{c,0} = u_c \cdot \lambda^2
  \]

- Effect of **electromechanical instability** occurs if:

\[
\frac{2 \cdot u_{c,0}}{Y} > \frac{\sigma_{elast}}{Y} + \frac{F_{\text{load}}}{A \cdot Y}
\]

- Instability **limits the maximum stretch** depending on the generated force

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2. Performance Limitations

- Depending on the exerted force the critical stretch and corresponding energy vary.
- Electromechanical instability limits the

- **Maximum No-Load-Stretch**
  \[ \lambda_{z,\text{crit}} \left( F_{\text{act}} = 0 \right) = \frac{3\sqrt{2}}{2} \approx 0.63 \]
  \[ u_{c,0,\text{crit}} \left( F_{\text{act}} = 0 \right) = \frac{3\sqrt{2}}{16} \approx 0.079 \]

- **Maximum Blocking-Force**
  \[ \frac{F_{\text{act}} \left( \lambda_{z,\text{crit}} = 1 \right)}{A_0 \cdot Y} = \frac{1}{3} \]
  \[ u_{c,0,\text{crit}} \left( \lambda_{z,\text{crit}} = 1 \right) = \frac{1}{6} \]
2. Design Optimizations – Conclusion

- Based on the static model of a DEAP stack-actuator the Blocking-Force and No-Load-Stretch were investigated

<table>
<thead>
<tr>
<th>Blocking-Force</th>
<th>No-Load-Stretch</th>
</tr>
</thead>
<tbody>
<tr>
<td>$F_{\text{act}} \uparrow$ with $u_c \uparrow$</td>
<td>$\Delta l \uparrow$ with $u_c \uparrow$</td>
</tr>
<tr>
<td>$F_{\text{act}} \uparrow$ with $A_0 \uparrow$ ($A_0$: free design parameter)</td>
<td>$\Delta l \uparrow$ with $Y \downarrow$, $l_0 \uparrow$ ($Y$: material parameter $l_0$: free design parameter)</td>
</tr>
</tbody>
</table>

Electromechanical Instability

$F_{\text{act}} \left( \lambda_{z,\text{crit}} = 1 \right) = \frac{A_0 \cdot Y}{3}$

$F_{\text{act}} \left( \lambda_{z,\text{crit}} = 1 \right) \uparrow$ with $A_0, Y \uparrow$

$\lambda_{z,\text{crit}} \left( F_{\text{act}} = 0 \right) \approx 0.63$

$\Delta l \uparrow$ with $l_0 \uparrow$

optimal operation point $\Rightarrow \kappa = f \left( u_c \right)$

maximum electromechanical coupling $\Rightarrow \lambda_{z,\text{opt}}$

\[ \Delta l = \left( 1 - \lambda_z \right) \cdot l_0 \]
3. DEAP stack-actuator design

- Increase of absolute deformation and force → multilayer actuator
- By **stacking** the actuator films to the designated height and **alternating the direction of the contact tab**, the DEAP stack-actuator is obtained.

![Diagram of DEAP stack-actuator design](image)

\[
\sigma_{el} = \varepsilon_0 \varepsilon_r \frac{V^2}{t^2}
\]

4. Manufacturing of DEAP Stack-Actuators

- Dry deposition process:
  - divided into several processing steps
  - fabricate stack-actuators with reproducible and homogeneous properties
4. Manufacturing of DEAP Stack-Actuators

Sub-process 2: applying electrodes and folding

- DEAP film is fixed on the vacuum folding table
- a mask is positioned over the elastomer
- a nozzle is positioned over several sectors and electrodes are applied
- DEAP film with the applied structured electrodes is folded

⇒ after 4 spraying and 3 folding processes an actuator module is created whose thickness is 8 times higher than the single film

⇒ due to the very thin DEAP films, the films are folded to facilitate the handling
4. Manufacturing of DEAP Stack-Actuators

Sub-process 3: stacking of DEAP sub-modules to designated height

- Folded DEAP film module is lifted by the vacuum gripper.
- Folded DEAP film module is transported to the film carrier of the rotary index table.
- Folded DEAP film module is stacked and laminated on top of each other.
4. Manufacturing of DEAP Stack-Actuators

Sub-process 4: cutting by a ultrasonic knife to separate DEAP stack-actuators

- Stacked DEAP film module is fixed and transported by the film carrier of the rotary index table
- Individual actuator modules are cutted out
- Individual actuator modules are separated
4. Contacting of the DEAP stack-actuator module

- To realize a transition from the elastic DEAP to the stiff wiring of the power electronics, a DEAP contacting film is used, which does not harm the actuation.
- To protect the DEAP stack-actuator against environmental influences, the actuator is encapsulated by winding a polymer film around the stack-actuator.

a) contacting pins are rolled into the contacting film  
b) wound around the actuator module in a pre-stretched condition  
c) end cap with grooves is applied to fix the contacting pins  
d) a polymer film is wound around the stack-actuator

4. Experimental validation of the actuator design

DEAP stack-actuator

“No-Load-Stretch” behavior of the produced DEAP stack-actuator:

Parameters of the stack-actuator:

\[ t_0 = 50\text{µm}; \; Y = 3\text{MPa}; \; \varepsilon_r = 7; \; N = 160 \]
5. Conclusion

- DEAP transducer can be used as actuators, sensors and generators
- Based on an analytical model of a DEAP stack-actuator design rules can be obtained.

DEAP technology is an energy efficient alternative for conventional actuators with further excellent properties.

However, concerning the material and the manufacturing a lot of R&D has to be done.
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Thanks for your kind attention!

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