The Need of Advanced Techniques for Manufacturing

Piezocomposite and Piezoelectric Actuator Design

Emilio Silva and Noboru Kikuchi
Materials Opportunities in Layered Manufacturing Techniques
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Major Collaborators

Professor Emilio C.N. Silva
Mechanical Engineering
University of Sao Paulo, Brazil

Professor John Halloran, A.T. Crumm, G.A. Brady
Material Science and Engineering
The University of Michigan

Professor F. Montero de Espinosa
Instituto de Acustica, Madrid, Spain
Homogenization Design Method

- Shape and Topology Design of Structures is transferred to Material Distribution Design (Bendsoe and Kikuchi, 1986)
HDM : 3D Shaping

Truly Three-dimensional shaping of a structure for optimum

Requirement of emerging manufacturing methods
Extension of HDM

- Structural Design
  - Static and Dynamic Stiffness Design
  - Control Eigen-Frequencies
  - Design Impact Loading
  - Elastic-Plastic Design

- Material Microstructure Design
  - Young’s and Shear Moduli, Poisson’s Ratios
  - Thermal Expansion Coefficients

- Flexible Body Design
New Extension of HDM

Piezocomposite
and
Piezoelectric Actuator
Design
Introduction

Force
Mechanical Energy
Displacement

Piezoelectric Material

Electric potential
Electrical Energy
Electric charge

Examples: Quartz (natural)
Ceramic (PZT5A, PMN, etc…)
Polymer (PVDF)
Applications

Pressure sensors
accelerometers
actuators,
acoustic wave generation
  ultrasonic transducers, sonar, hydrophones
etc...
Constitutive Equations of Piezoelectric Medium

\[
\begin{align*}
T_{ij} &= c_{ijkl}^E S_{kl} - e_{kij} E_k \\
D_i &= \varepsilon_{ik}^S E_k + e_{ikl} S_{kl}
\end{align*}
\]

- $T_{ij}$ - stress
- $S_{kl}$ - strain
- $E_k$ - electric field
- $D_i$ - electric displacement

$c_{ijkl}^E$ - stiffness property
$e_{ikl}$ - piezoelectric strain property
$\varepsilon_{ik}^S$ - dielectric property
Introduction - Piezocomposites

Combination of a piezoelectric material with other non-piezoelectric materials (ex.: holes)

Advantages: high energy conversion, low acoustic impedance, etc...
Design Practice: Parametric

Piezocomposite Moonie transducer

Change parameter

Verify improvement (FEA, experiment)

$L_1$  $L_2$

$D$

$h_1$

$h_2$

Coupling Structure

PZT
Mathematician Changes Design Practice

Using Parametric Analysis:

- Influence of volume fraction, Poisson’s ratio, etc…: Smith (1993), Avellaneda and Swart (1994)
- Use of negative Poisson’s ratio material: Smith (1991), Avellaneda and Swart (1994)
- Porosity in the matrix polymer: Avellaneda and Swart (1994)
Topology Design

- Change the topology of microstructure (material) or structure (transducer)
- Improvement in the performance of piezocomposite materials; design of new kinds of transducers for different applications
Many Approaches: HDM

Simple: Density Method

\[ E_{ijkl} = x^p E_{ijkl}^0 \]

fraction of material in each point

Material Design

General: Homogenization Method

A point with material

A point with no material

Structure Design

property

Structure Design Domain \( \Omega \)

A point with no material

A point with material

Microstructure

\[ 1 \]

\[ \theta \]

\[ a \]

\[ b \]
Homogenization in Piezoelectricity

- Telega (1990), Galka et al. (1992), and Turbé and Maugin (1991)
- Asymptotic analysis
- Periodic microstructures, scale of microstructure very small compared to the size of the part
- Acoustic wavelength larger than unit cell dimensions
Maximize: $F(x)$, where $x = [x_1, x_2, \ldots, x_n, \ldots, x_{NDV}]$

subject to:

- $c_{ijkl}^E \geq c_{\text{low}}$, i, j, k, l are specified values
- $0 < x_{\text{low}}^{NDV} \leq x_n \leq 1$
- $W = \sum_{n=1}^{NDV} x_n^p V_n > W_{\text{low}}$

symmetry conditions

$F(x)$ - function of $d_h$, $d_{gh}$, $k_h$, or $k_t$

$x$ - design variables

$W$ - constraint to reduce intermediate densities

($V_n$ - volume of each element)
The University of Michigan Computational Mechanics Laboratory

- Initializing and Data Input
- Obtaining Homogenized Properties
- Converged?
  - Y: Plotting Results
  - N: Calculating Sensitivity

- Updating Material Distribution
- Optimizing (SLP) with respect to $x$
- Initial Guess
- Final Topology
Reference unit cell for comparison: 2-2 piezocomposite

PZT5A
Polymer (Spurr)

(Poled in the 3 direction)
2D Piezocomposite Unit Cell
hydropone

Initially

Optimized Microstructure

Piezocomposite

polymer

air

Suggested Transducer
Improvement in relation to the 2-2 piezocomposite unit cell:

- $|d_h|$: 2.8 times
- $d_h g_h$: 7.1 times
- $k_t$: 1.13 times

$\rho \downarrow \Rightarrow Z \downarrow \quad v_t (\cong \text{same})$

Stiffness constraint: $c_{11}^E > 8.10^8 \text{N/m}^2$
Experimental Verification

- Rapid Prototyping: Stereolithography Technique

Optimized Transducer

Reference Transducer
Experimental Result

Measured Performances

<table>
<thead>
<tr>
<th></th>
<th>$d_h (pC/N)$</th>
<th>$d_h g_h (fPa^{-1})$</th>
<th>$k_t$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Reference</td>
<td>9.1</td>
<td>13.2</td>
<td>0.69</td>
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<tr>
<td>Optimized</td>
<td>246.</td>
<td>10400.</td>
<td>0.70</td>
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<tr>
<td>(Simulation)</td>
<td>(229.)</td>
<td>(10556.)</td>
<td>(0.66)</td>
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</tbody>
</table>
2D Piezocomposite Unit Cell
hydrophone

Initially                  Optimized Microstructure                  Piezocomposite

PZT5A

air

PZT5A

3

1

“optimized porous ceramic”
Improvement

Improvement in relation to the 2-2 piezocomposite unit cell:

\[ |d_h|: \text{ 3. times} \]
\[ d_hg_h: \text{ 9.22 times} \]
\[ k_h: \text{ 3.6 times} \]

stiffness constraint: \( c_{33}^E > 1.10^{10} \text{N/m}^2 \)
Piezocomposite Manufacturing

Microfabrication by coextrusion technique

Theoretical unit cell

Fugitive

Ceramic
Ceramic Feedrod Reduction Zone Extrudate

Crumm and Halloran (1997)
3D Piezocomposite

Reference unit cells: 1-3 piezocomposite

Similar Behavior for $d_h, g_h, k_h, \text{ and } k_t$
3D Piezocomposite Unit Cell
hydrophone

Piezoceramic

Poled in the z direction
3D Piezocomposite Unit Cell
hydrophone

Polarized in the z direction

piezoceramic
Summary

We have shown that
Layered Manufacturing Method
open up possibility of
topology design of piezoceramic composites
and piezoelectric actuators
for large scale performance improvement
by the homogenization design method