Towards the development of a MEMS-based health monitoring system for lightweight structures

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Introduction and motivation

MEMS accelerometers for structural health monitoring (SHM): why?

**PROS**
- lightweight (0.2 g) → no impact on dynamics
- low power consumption
- cheap (0.50$ each!) → deploy in large numbers
  → use redundancy to increase the quality of information

**CONS**
- noisy signals, low precision

![Graph showing acceleration data over time]
Outline of the research project

Aim: a **SHM system** using MEMS

Focus of the presentation

- assessment of MEMS applicability
- sensor placement strategy
Features of 3-axis, digital output MEMS (micro electro-mechanical sensor) accelerometer **LIS3LV02DQ** (STMicroeletronics):

- full scale $\pm 2g$
- bandwidth 640 Hz
- sensitivity 1,000 LSb/(Least_Significant_bit)/g
- resolution 1 mg
- weight 0.2 grams
- side: $\sim 5$ mm
Preliminary analysis: test specimens

Standard DCB ...

[Diagram of DCB test specimen with labeled dimensions and components]
Preliminary analysis: test specimens

...and ELS test specimens
Test #1: DCB test under continuously increasing displacement

Fair correlation between load drops and acceleration peaks

Fair correlation between load drops and acceleration peaks.
test #2: tests under cyclic loading

**Input:** Sinusoidal displacement $u$

(at increasing $u_0$, $\Delta u = 2.5$ mm, frequency = 0.5 Hz, 200 cycles)
Load $P$ suffers drops because of delamination growth at the beginning of load steps.
test #2: DCB acceleration output

The acceleration, $a_x$, is too noisy to reliably determine the crack length.
test 2#: simple sensing system for DCB specimens

but taking the Fourier transform $F[a_x]$ of the signal

\[ F[a_x] \]

| $|F[a_x]|$ [m/s] |
|------------------|
| $f$ [Hz]         |

<table>
<thead>
<tr>
<th>Boundary displacement frequency</th>
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<tbody>
<tr>
<td>$a = 52$ mm</td>
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<tr>
<td>$a = 75$ mm</td>
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<tr>
<td>$a = 81$ mm</td>
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<tr>
<td>$a = 105$ mm</td>
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| $|F[a_x]|(f_{test})$ [m/s] |
|-------------------------|
| delamination length [mm]|

$k/a^{2.6}$
ELS: mean rotation

\[ \phi = \frac{d\varphi}{dx} \approx \arctan \frac{\alpha_x}{\alpha_z} \]
Optimal sensor placement

- **Topology approach**: define a density distribution $\mathbf{x}$ representing sensor position and optimize it in order to make damage detection easier.

- **Finite elements (FE)** for structural analysis (plates)

- **Method of moving asymptotes (MMA)** for optimization

\[
\begin{align*}
\max_{\mathbf{x}} & \sum_{i=1}^{n} x_i (u_i - \hat{u}_i)^2 \\
\text{s. t.} & \quad \sum_{i=1}^{n} x_i \leq N \\
& \quad 0 \leq x_i \leq 1 \quad i = 1, \ldots, n
\end{align*}
\]

- Penalization term to approach pure 0-1 distributions

- Undamaged plate solution

- Damaged plate solution

- Number of possible sensor locations (FE)

- Max allowed number of sensors
In case of a **multiple damaged regions** (and/or unknown position), to maximize the **sensitivity** to the magnitude of the effects of damage [FORM-1]:

\[
\max_x \sum_{k=1}^s \left[ \sum_{i=1}^n x_i^p (u_{ki} - \hat{u}_i)^2 \right]
\]

s.t.
\[
\sum_{i=1}^n x_i \leq \bar{N}
\]
\[
0 \leq x_i \leq 1 \quad i = 1, \ldots, n
\]

or, to maximize the **sensitivity** to damage [FORM-2]:

\[
\max_x \sum_{k=1}^s \left[ \frac{\sum_{i=1}^n x_i^p (u_{ki} - \hat{u}_i)^2}{\max_i x_i^p (u_{ki} - \hat{u}_i)^2} \right]
\]

s.t.
\[
\sum_{i=1}^n x_i \leq \bar{N}
\]
\[
0 \leq x_i \leq 1 \quad i = 1, \ldots, n
\]
Simply supported plate, distributed load

damage can be anywhere, known size (1 FE)

\[ \overline{N} = 5 \]

\[ \overline{N} = 50 \]

(FORM-1)

(FORM-2)

(Mariani et al., JIMSS 2013;24:1105)
effect of damage area

simply supported plate, distributed load

damaged area

1 × 1 •
1 × 2 -
2 × 2 ■
4 × 4 □
Multi scale approach

clamped plate, concentrated load, [FORM-2],

Multi-scale analysis: $L=1\,\text{m}$ (side length, or structural size)
$s=5\,\text{cm}$ (element, or damaged area size)
$l=2.5\,\text{mm}$ (sensor size)
In conclusion...

- We proposed a MEMS-based SHM system, sensitive to damage (delamination) extent in composite
- We proposed a (possibly multi-scale) topology optimization-like procedure to deploy MEMS, so as to maximize sensitivity to damage

Ongoing activities and future work

- real-time damage detection and identification for flexible (composite) plates
- minimization of $\bar{N}$
- Application: engineered bike and ski helmets (to understand links between impacts and brain injuries)

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