INTELLIGENT STRUCTURES TECHNOLOGY

Edward F. Crawley

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Overview

- Embedding electronic components for control of intelligent structures.
- Single-chip microcomputer control experiment
- Structural shape determination
- Distributed sensor systems for structural control
Motivation

- Precision control of flexible structures is more readily achieved with large numbers of sensors and actuators
- Signal quality can be improved by distribution of analog processing circuitry along with transducers
- Connectivity (number of lines) can be greatly reduced by distribution of A/D, D/A conversion with digital bus interface circuitry
- Control loop speed can be substantially elevated by distribution of digital processors in a hierarchic controller

Missing element in fully integrated intelligent structures concept: embedded electronics
Objectives

Establish the feasibility of physically embedding electronic components for the control of intelligent structures.

Demonstrate structural control using processor with minimal number of chips.
Embedding Electronics: Approach

- Select a suitable candidate chip for embedding
- Develop embedding technique
- Test mechanical static and fatigue properties
- Test temperature-humidity-bias reliability
Electrical and Mechanical Compatibility

Issues:

- Manufacturing - autoclave pressures and temperatures

- Operational mechanical stress – brittle Si, delicate SiO₂ and metal structures

- Electrical insulation from graphite fibers

- Ionic contamination – device lifetime is typically limited by corrosion

- Minimal disruption of structural plies
Integrated Circuit Chip Packaged for Embedding

Dielectric integrated circuit sensor (Micromet Instruments, Inc.)

Circuit area consists of two metal-oxide-semiconductor field effect transistors and one diode

Packaging is similar to Tape Automated Bonding (TAB)
Integrated Circuit Chip Packaged for Embedding

- Polyimide
- 8.9 mm
- 0.5 mm

- Sensing region
- 11.1 mm
- Circuit region
- Dielectric sensor chip
- Protective epoxy layer

- Copper leads (356 mm overall)
- RTV layer

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Embedding Devices within Composite Structures

Layup is $[0/90/0_2]_S$
Test of Embedded Circuit in G/E Coupon

With epoxy protective layer

Device failure at 750 MPa
Test of Embedded Circuit in G/E Coupon

---long. far field ---long. side ---long. over chip

device failure at 1150 MPa

With RTV isolation layer

Stress (MPa)

0 200 400 600 800 1000 1200 1400

0 2500 5000 7500 10000 12500 15000

Strain (μstrain)
Temperature/Humidity/Bias Test

- Test conditions:
  3 chips embedded in 60 mm x 75 mm laminates subjected to 80°C and 80% R. H. for 125 hours
  Transistor drain-source currents while under constant bias continuously monitored; characteristic curves recorded at log time intervals
  Two conventional MOSFETs included as experimental controls

- Results:
  One sensor showed intermittent anomalies (hysteresis, elevated current) as early as 14 hours - possible leakage currents through epoxy
  One sensor showed progressive drop in current during final 4 hours - consistent with lead corrosion
  One sensor showed no anomalies
  Conventional controls showed no anomalies
Single-chip Microcomputer Control Experiment
Performance Achieved

Magnitude of Disturbance Transfer Function

Increased damping: 1st mode 0.36% OL 31% CL
2nd mode 0.15% OL 4% CL
3rd mode 0.20% OL 11% CL
Major Results

- Embedding electronics is feasible
  Compliant isolation layer allows device function to laminate failure
  Chemical isolation is inferior to commercial devices, requires further work
  All failures were at or near lead-chip bond

- Embedding local processors are plausible
  Distribution of processing can be justified, depending on problem size
  Nearly all of the required functions included on currently available monolithic devices
Structural Shape Determination Objectives

Objective is to determine "optimal" type and number of sensors to allow accurate reconstruction of structural shape from discrete curvature measurements.

Issues considered include:

- Accuracy of predicted slope and displacement for various integration rules as a function of the number of gages.
- Static and dynamic mode shape determination with strain averaging sensors.
- Frequency characteristics of a single sensor.
- Frequency characteristics of integrated shape measurement.
Approach to Integration Rule Study

- Consider a cantilevered beam subjected to a representative set of simple static loadings.
- Distribute a set of strain gages along the length of the beam.
- Integrate the curvature using a variety of integration rules to obtain an estimate of the shape of the beam.
- Vary gage factor and gage placement to obtain error bounds for experimental uncertainties.
- Compare performance of short and long gages to determine whether a "point" or an averaged strain measurement yields better performance.
Deflection Prediction Error vs Number of Gages

Spline integration rule and long gages

Solid line: No gage factor or placement error.
Dashed line: 1% gage factor error and placement error of 0.2% of the beam length.
Dot-dashed line: 5% gage factor error and placement error of 1% of the beam length.

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Functional Requirements for Distributed Sensor Systems

- The sensors should be able to sense static modes and resolve them in detail.
- The integral of the static shape, and therefore output of each sensor should roll off quickly in frequency and not have negatives.
- The sensors must have good observability of the dynamic modes targeted for control in the bandwidth.
- The observability of dynamic modes must roll off quickly beyond the control bandwidth.
- The sensors should be easily implementable and must be finite in length.
- If possible, the sensors should not contain negative regions.
**Approach**

- Consider a pinned-pinned beam with 9 gages distributed along its length.
- Vary the length and spatial weighting of the gages.
- Integrate the sensor measurements to obtain an estimate of the shape of the beam.
- Increase the frequency of the dynamic mode of the beam, and examine the behavior of the tip deflection estimate.
- Verify that observability rolls quickly and monotonically approaches zero.
- Optimize the roll off characteristics by varying spatial weighting of the sensors.
# Examples of Single Sensor Characteristics

<table>
<thead>
<tr>
<th>Shape</th>
<th>Advantages</th>
<th>Disadvantages</th>
</tr>
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<tbody>
<tr>
<td>Sinc</td>
<td>Gives perfect rolloff with no phase lag.</td>
<td>Is of infinite extent in ( x ).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Has negative regions in ( x ).</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hard to manufacture and distribute.</td>
</tr>
<tr>
<td>Rectangle</td>
<td>Very simple shape.</td>
<td>Only -20 db/decade rolloff.</td>
</tr>
<tr>
<td></td>
<td>Can be distributed easily.</td>
<td>Has large negative regions in ( k ).</td>
</tr>
<tr>
<td>Gauss</td>
<td>Has no negative regions in ( x ) or ( k ).</td>
<td>Is of infinite extent in ( x ).</td>
</tr>
<tr>
<td></td>
<td>Has good rolloff (-300 db in 1st decade).</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Can be distributed.</td>
<td></td>
</tr>
<tr>
<td>Hanning(^2)</td>
<td>Has no negative regions in ( x ).</td>
<td>Has small negative regions in ( k ).</td>
</tr>
<tr>
<td></td>
<td>Has good rolloff (-100 db/decade)</td>
<td></td>
</tr>
<tr>
<td></td>
<td>Can be distributed.</td>
<td></td>
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Fourier Transforms of Rectangular, Gaussian and Hanning Squared Windows

- Rectangular Window
- Gaussian Window
- Hanning Squared Window

Magnitude vs. Wavenumber
Error vs. Mode Number (Rolloff at mode 4)

Gage shape: Gaussian

x/L along beam with 9 gages

Mode number

Amplitude

(%) Error

100
50
0
Error vs. Mode Number (Rolloff at mode 3)

Gage shape: Hanning * Hanning

x/L along beam with 9 gages
Conclusions

- Numerical integration schemes have been found that yield accurate shape prediction with a minimum of sensors.

- Spatial weightings for distributed sensors have been identified that yield quick rolloff in:
  - Individual outputs of each sensor
  - Integrated output of all the sensors (tip displacement)

- The functional requirements can nearly be met by simple sensor shapes that are relatively easy to implement.

- Meaningful experiments must be carried out in order to verify theoretical predictions and determine sensitivity of performance to errors incurred during physical implementation of a distributed sensor system.