Fiber optical current sensors and stress sensors based on magnetostrictive composites

Chiu T Law, Electrical Engineering
Rani El-Hajjar, Civil & Environmental Engineering
(co-directors of smart composites and sensors lab)

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Overview

• Magnetostriction, Villari effect and composites.

Components of fiber optical current sensor (FOCS).

• FOCS configurations and results

Uniqueness of FOCS.

• Future method for magnetostrictive device fabrication.

Magnetostrictive stress sensors.

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Magnetostriction and Villari effect

• Expansion along magnetic field $H$.
• External stress leads to domain rotation.
• Such rotation changes magnetic properties of the material.
• Same material exhibits inverse magnetostriction.
• Giant magnetostrictive material used here.
• Length increases.
• Cross section contracts as the direction (easy axis) is proportional to $H$ magnitude but not $H$ polarity.

Terfenol-D (T-D) (https://en.wikipedia.org/wiki/Magnetostriction)

Magnetostriction

Villari effect
Comment on Composites

Fiber Bragg Grating (FBG)

Grating length \( L \)
- Reflection power depends on period \( \Lambda \).
- Is determined by the grating
- Bragg (reflected) wavelength \( \lambda_B \)
- Wavelength selective mirror

\[ \lambda_B = \frac{2n \Lambda}{\Lambda - \Lambda} \]

Mainly epoxy composites:
- There are other possibilities.

Sensitivity is lower:
- Sensors can be embedded.
- Easier to be molded into any shape.
- Frangible of T-D is mitigated.
- Faster response can be achieved.
- Insulator-coated T-D particles.
- Eddy current loss is reduced with
- Less expensive material is used.

Composite and Fiber Bragg Grating (FBG)
Fiber Optical Current Sensor (FOCS)

- Form novel FOCSs by integrating FBG (strain distribution sensor) with magnetostrictive composite (transducer).
- Infer electric current (DC and AC) by sensing magnetic field surrounding a conductor for fault detection.
- Require simple optical measurements.
- Have fast response and compact transducer design to translate magnetic field information into optical signal.
- Ready for formation of sensor network for current measurements at various locations with a single fiber.
- Has EMI immunity, i.e., no heavy insulation for high voltage and current.
- Require simple optical measurements.
- Form novel FOCSs by integrating FBG (strain (transducer)).

Fiber Optical Current Sensor (FOCS)
Chirped FOCS (4 Components)

- At $H=0$, FBG has uniform period.
- Measure strain with FBG bandwidth induced by the formation of chirped FBG that is aperiodic.
- Protect sensor with packaging.
- Compensate for thermal drift with MONEL-400.

*Note: Diagram shows a schematic representation of the components and their arrangement.*
Chirped FOCS Embedded in a Composite

- Low component count (two) and robust.

- No thermal compensation required (thermally independent of FBG bandwidth).

- Graded Terfenol-D composite

- At \( H = 0 \), periodic FBG.

- Larger strain in dark region with larger particle size / concentration.

- Strain distribution inducing a chirped FBG with aperiodicity proportional to \( H \).

- No thermal compensation required (thermally independent of FBG bandwidth).
Chirped FOCS with Field Concentrator

- Shape the T-D composite to focus magnetic field to form a gradient
- Experiment (composite)
- Simulation (monolithic)

Volume fraction (VF) 106-300 μm.

Randomly oriented particles ranging from about 35%.

Sprayed painted with a sparkle pattern for digital image correlation (DIC).

- T-D composite cone with a flat top as the frequency chirping transducer

Field gradient: arrows H field, color B field.

Hole for FBG embedding.

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Model an axial hole to the cone.

Glass cylinder (FBG) at the hole center.

Epoxy layer between wall and FBG.

Independent on stiffness of the epoxy layer.

Verify insignificant thermal effect.

Epoxy layer between wall and FBG.

Glass cylinder (FBG) at the hole center.

Model an axial hole to the cone.

Axial strain distribution at various levels of H.

Strain Distribution Simulations
Place the cone between a pair of Helmholtz coils.

DIC image (Istra 4D software package).

Similar displacement fields (6x higher).

Simulation (monolithic)

Experiment (composite)
Optical Spectral Power

- Uniform strain distribution at high field
- Spectrum narrowing at high field
- Spectrum widen until \( H = 40 \text{kA/m} \)
- Spectrum widen at very low field
- Power decrease in high field
- No much change in power
- Initial strain from uneven attachment

Spectrum Change in Wavelength

<table>
<thead>
<tr>
<th>Percentage Change in Wavelength</th>
<th>0</th>
<th>0.02</th>
<th>0.04</th>
<th>0.06</th>
<th>0.08</th>
<th>0.1</th>
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<tbody>
<tr>
<td>Normalized Spectral Power</td>
<td></td>
<td></td>
<td></td>
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<tr>
<td>Simulation (monolithic)</td>
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<tr>
<td>Experiment (composite)</td>
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</tbody>
</table>

Attach an FBG through the central hole

\( 100 \text{kA/m} \)
\( 20 \text{kA/m} \)
\( 40 \text{kA/m} \)
\( 50 \text{kA/m} \)
\( \text{H=0} \)
\( 1.75 \text{kA/m} \)
\( 2.91 \text{kA/m} \)
\( 3.84 \text{kA/m} \)
\( 9.21 \text{kA/m} \)
\( 12.3 \text{kA/m} \)
\( 40 \text{kA/m} \)
Align T-D particles.

- Align T-D particles.
- of low viscosity.
- of the hole with uniform epoxy layer.
- Fill the gap between FBG and wall.
- To achieve results closer to simulation.

- Similar trend without initial drop.
- Small change in optical power.
- Almost linear increase when $H$ between 150 kA/m to 275 kA/m.

To achieve results closer to simulation:

- Fill the gap between FBG and wall with uniform epoxy layer of low viscosity.
- Align T-D particles.

Integrate each spectrum for total optical power.
Description

- T-D/epoxy composite strips mounted on surfaces of 6061-T6 aluminum substrates at various angles.
- Stress applied to ends of substrates.
- Sensor response (change in magnetic susceptibility) picked by a probe (toroidal coil with a gap) with LRC meter.
- Structural health monitoring applications in industrial, civil, and aerospace engineering.
- Multiple sensors for stress vector.
- Angle $\phi$ between sensor axis and force direction.
- Composite volume fraction (VF) 49% with low viscosity epoxy.
- Force applied to ends of substrates.
- Silicon Steel Core
- Toroidal Coil

Parameters

- Composite volume fraction (VF) 49%
- Stripe dimensions $l = 2 \text{.}11$ mm, $h = 2 \text{.}11$ mm, and $t = 1 \text{.}4$ mm.
- Angle $\alpha$ between sensor axis and force direction.
Sensor response compared to strain

Sensor response

Percentage change in magnetic susceptibility

\[
\frac{\Delta \chi_m}{\chi_m} \times 100\% = \frac{L_0 - L}{L_0} \times 100\%
\]

Verification of sensor response with strain rosettes

Responses almost linear.
Response to Stress as a function of stress

- Readings from load cell of load testing machine
- Strain rosette measurements
- Almost linear response confirmed

Fitting Function

\[
\chi = \frac{\Delta \chi}{\chi} \times 100\% = \frac{d\Delta \chi}{\chi} \nu
\]

Fitting Function

- \( \Delta \chi \) = 36\%
- \( \chi = 3.5\%
- \( \nu = 1.1 \times 10^{-8} \)
- \( \phi \)
- \( (C^2 + \phi \cos \theta) \)
- \( C^1 - \chi = d\Delta \chi \nu \)

Response to Stress as a function of stress
Effect of volume fraction.
- Superior performance of the 45° sample.

Orthogonal layers alternately explains the
- Default infill generation 3D printing
- Alignment effect.

Optical microscopy confirms particle
- Effect due to the printing process.

Volume fraction (some particle alignment
- Sample response for 45° sample at 1.5%

Magneostriptive response
- Its response.

3D print this composite, and characterize
- ABS acrylonitrile butadiene styrene

Printers by introducing T-D particles to
- Fused deposition modeling (FDM) 3D

Produce smart composite feedstock for
- Magnetic response of Magnetostrictive Composite

Sample layer section: 0° (L), 45° (R) infill angle
Villari: Response of 3D Printed Composite

- No apparent effect on sensitivity of particle alignment.
- Huge trial-to-trial variability in sensitivity for 5% volume fraction sample (agglomeration of T-D particles?).
- Linear responses within the test range (3.6 MPa).

Leads to LCR meter

0
0.5
1
1.5
2
ΔX_m per unit stress

Deep
5% VF 0

Deep
5% VF 45

Deep
15% VF 0

Deep
15% VF 45

Grip
Stand
coil
pickup
Sample
Summary

• Demonstrate magnetic field sensing with chirped FOCS based on magnetostrictive effect.
• Need to improve FBG attachment.
• Work to optimize FBG designs.
• Demonstrate magnetic field sensing with chirped FOCS based on inverse magnetostrictive effect.
• Fabricate magnetostrictive-ABS feedstock for FDM 3D printing.
• Find almost linear response that can be captured by a remarkably close fitting function.
• Print magnetostrictive samples and characterize their responses.
• Observe particle alignment by the printing process.

Fabricate magnetostrictive-ABS feedstock for FDM 3D printing.
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Contact Information

20

University of Wisconsin-Milwaukee
College of Engineering & Applied Science
Department of Civil & Environmental Engineering
Associate Professor
Rani Elhajjar (elhajjar@uwm.edu)

University of Wisconsin-Milwaukee
College of Engineering & Applied Science
Department of Electrical Engineering and Computer Science
Associate Professor
Chiuc T Law (lawc@uwm.edu)