Pipeline Corrosion Monitoring by Fiber Optic Distributed Strain and Temperature Sensors (DSTS)

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Fiber Optic Sensors

- Advantage of fiber optic sensors
  - Electrically insulating materials (no electric cables are required) — high voltage environments
  - Chemically passive, not subject e.g. to corrosion
  - Immune to electromagnetic interference (EMI)
  - Wide operation temperature range
- Fiber Bragg Grating Sensor
  - Strain resolution and accuracy: < 1 me
  - Non-distinguishable between strain and temperature
  - Point sensor
- Distributed Fiber Optic Sensors
  - Raman scattering based — only temperature
  - Brillouin scattering based — both temperature and strain
Working Principle — BOTDA
(Brillouin Optical Time Domain Analyzer)

When the beat frequency $v_{1}-v_{2}$ matches the intrinsic Brillouin frequency of the fiber, we will get the maximum of the Brillouin spectrum.

The Brillouin frequency $v_B$ changes linearly with the strain and temperature exerted.

$$v_B = v_{B0} + C_T(T - T_0) + C_\varepsilon(\varepsilon - \varepsilon_0)$$

Profile

Sensor medium: standard telecom optical fiber

Loss

Brillouin Spectrum
Working Principle — BOTDA (cont’d)

\[ \nu_B = \nu_{B0} + C_T (T - T_0) + C_\varepsilon (\varepsilon - \varepsilon_0) \]
Working Principle — Coherent interaction of pulse and pump lights

Numerical model of P/P-based Brillouin Fiber Sensor

\[
\left( \frac{\partial}{\partial z} - \frac{1}{v_g} \frac{\partial}{\partial t} \right) E_p = ig_1 Q E_s + \frac{1}{2} \alpha E_p
\]

\[
\left( \frac{\partial}{\partial z} + \frac{1}{v_g} \frac{\partial}{\partial t} \right) E_s = -ig_1 Q^* E_p - \frac{1}{2} \alpha E_s
\]

\[
\left( \frac{\partial}{\partial t} + \Gamma \right) Q = -ig_2 E_p E_s^*
\]

Three coupled differential equations:

* Two Maxwell’s equations describing the propagation of the Stokes and pump laser beams
* A simplified Navier-Stokes equation describing the density wave

\[ a = \text{fiber absorption} \]
\[ E_p = \text{pump field} \]
\[ E_s = \text{Stokes field} \]
\[ Q = \text{acoustic field} \]
\[ v_g = c/n \]
\[ G = G_1 + iG_2 \]
\[ G_1 = 1/2 \tau \]
\[ G_2 = \omega - \omega_B \]
\[ \Gamma \]
\[ g_1, g_2 : \text{coupling constants} \]
\[ g_B = 2g_1g_2/G_1 \]
\[ \text{Brillouin gain} \]
Working Principle — Coherent interaction of pulse and pump lights (cont’d)

Numerical simulations
Pulse: 1.5 ns
Linewidth: 46, 58, and 952 MHz
for ER=15 dB, 20 dB, and infinite

Experimental results
Pulse: 1.5 ns
Linewidth: 46 and 56 MHz
for ER=15 dB and 20 dB
Applications

- Oil and Gas Pipeline Monitoring
- Dam Monitoring
- Oil and Gas Well Monitoring
- Bridge and Building Monitoring
- Power Line Monitoring
- Border Security Monitoring
- Crack Detection
Optical fiber layouts & sizes of depleted regions

<table>
<thead>
<tr>
<th>Curve</th>
<th>Location (o'clock)</th>
<th>Reduced thickness (%)</th>
<th>Width (cm)</th>
<th>Length (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>5-7</td>
<td>60</td>
<td>5.3</td>
<td>61</td>
</tr>
<tr>
<td>C</td>
<td>7</td>
<td>50</td>
<td>1.3</td>
<td>10</td>
</tr>
<tr>
<td>D</td>
<td>5</td>
<td>60</td>
<td>1.3</td>
<td>10</td>
</tr>
</tbody>
</table>

Cross sections: lime green

Bottom half of pipe

Dock position

- Thermocouples
- Sensing fibres (solid)

Bottom half of pipe

Dock position

- Thermocouples
- Sensing fibres (solid)
Spectrum Shape

- The spectrum in the perfect region exhibits higher intensity
- Fiber experiences higher bending loss in defective region
- Coherent interaction of probe and pump lights produces complex spectrum
- These differences can be used to identify defective regions
Axial strain distribution — along the pipe under 200 psi internal pressure

- Maximum strain (46 me) occurs in the middle of defect A.
- Minimum strain (14 me) happens in the middle of unperturbed region B.
- The support points, end-caps, asymmetric defect distribution affect axial strain distribution in both end of pipe.
Axial strain-pressure slopes — along the pipe

- Maximum 0.48 me/psi near the middle decreases toward the edges of defect A.
- Slope remains constant at 0.16 me/psi near the middle of unperturbed region B.
- Local stress concentration and overlapping 13 cm pulse lead to ripple from 70 to 100 cm.
Comparison of axial strain

- Defects A (60%) & C (50%) & region B (0%)
Hoop strain distribution

Hoop strain distributions around one pipe circumference encompassing defective region A (60% depleted wall, 5.3 cm wide and 61 cm long). Two maximal strains, corresponding to one complete loop, are observed.
Comparison of hoop strain
— around defects $C$ (50%) & $D$ (60%)
Pipeline erosion monitoring by DSTS

\[ \varepsilon \propto \frac{p}{H} \]
Conclusion

• A fiber optic distributed strain and temperature sensor (DSTS) has been used to identify several inner wall cutouts in an end-capped steel pipe successfully.
• Larger strains are observed in the big defective region.
• Between the small defective regions, the 60% depleted wall experienced larger strains than the 50% depleted wall.
• DSTS has been used to identify wall thickness change of steel pipe caused by oil sand erosion successfully.
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Thank You for Choosing OZ Optics

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