Sensitivity and Performance Characterization of Fiber Optic Cables for Near-Static Strain Sensing Applications

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Agenda

- Strain Sensing with Optical Fiber
- Challenges in Strain Sensing using Downhole Fiber Cable
- Lab-Based Characterization of Cables
- Field-Based Characterization of Cables
- Conclusion
Strain Coupling

- Near-Static Strain (Cross-well Monitoring)
  - Slow-changing strain monitored over 1 to 4 hours
  - Strain Rate: ~10 nε every 10 sec
  - Signal Frequency: <0.1 Hz (LF-DAS)

- Dynamic Strain (Microseismic)
  - Short lived events (< 1 sec)
  - Amplitudes typ. <30 nε
  - Signal Frequency: 10 Hz to 1000 Hz

SPE-209121-PA LeBlanc, et. al. (2022)
Maximum Strain Gradients

\[ \frac{d\varepsilon}{dz}_{\text{max}} = \mu \cdot K_{\varepsilon F} \cdot \left( w_{\text{cable}} - \rho_{\text{fluid}} g \left( \frac{\pi D_c^2}{4} \right) \right) \]

Grease layer on fiber improves coupling.

SPE-209121-PA LeBlanc, et. al. (2022)
Electrical Strain Gauge

Indicated strain:

$$\varepsilon_x = \frac{F \Delta R}{R}$$

Error due to temperature (thermal output):

$$\delta\varepsilon_{x,\Delta T} = \left[K\Omega + F \left(\frac{1 + K_t}{1 - \nu K_t}\right) (\alpha_s - \alpha_G)\right] \Delta T$$

Error due to transverse cross-sensitivity:

$$\delta\varepsilon_{x,y} = K_t (\varepsilon_y - \nu\varepsilon_x)$$

Other influence of life & performance:

- Bonding quality (coupling)
- Environment (moisture, high T)
- Cable / leads
- Interrogator (strain reader)

(Note: Would also be influenced by pressure $P$)
Fiber Optic Strain/Temperature Sensor

- Convenient to define “optical strain” as $\varepsilon_{opt} = \frac{\Delta \phi}{\phi_0} = \frac{\Delta (nL)}{nL_0} = \frac{\Delta (n\Lambda)}{n\Lambda_0} = \frac{\Delta \lambda}{\lambda_0}$

$$\varepsilon_{opt_{1,2}} = \varepsilon_z' - \frac{n^2}{2} \left[ p_{11} \varepsilon_{t_{1,2}}' + p_{12} (\varepsilon_{t_{1,2}}' + \varepsilon'_z) \right] + \left( \alpha_f + \frac{1}{n} \frac{\partial n}{\partial T} \right) \Delta T$$

Most commonly $\varepsilon_{t_1}' = \varepsilon_{t_2}' = \varepsilon_r' = -\nu_f \varepsilon_z'$ (Poisson ratio), hence:

$$\varepsilon_{opt} = \left( 1 + \frac{n^2}{2} \left( p_{12} - \nu_f (p_{11} + p_{12}) \right) \right) \varepsilon_z' + \left( \alpha_f + \frac{1}{n} \frac{\partial n}{\partial T} \right) \Delta T$$

$\equiv g \approx 0.8 \times 10^{-6}/\mu\varepsilon \quad \approx 8.5 \times 10^{-6}/^\circ C$

$\varepsilon_i'(\sigma, T, P) = \varepsilon_i - \alpha_f \Delta T$

elastic strain = total strain - fiber thermal expansion

$\Rightarrow 1^\circ C \approx 10 \mu\varepsilon$

(a change of 1$^\circ$C on a free fiber causes same signal shift as would adding 10 $\mu\varepsilon$)

$AB = 1 \text{ cm}$

$\phi_0 = \frac{4\pi(n_0L_0)}{\lambda}$

$L_0 = \text{gauge length (DAS)}$

$\Delta \phi = \frac{4\pi \Delta (nL)}{\lambda}$

$\lambda_B = 2n\Lambda$

$\Delta \lambda_B = 2\Delta (n\Lambda)$
Challenges for a Downhole Cable

- For permanent installation, fiber needs to be “encased” for protection (e.g., in metal tube)
- Static fatigue: Tension in fiber causes growth of microcracks on fiber glass surface
  - Reduces fiber strength
    - Fiber proof-test sets maximum crack length (minimum fiber strength, e.g. 100ksi, or 200ksi).
    - Crack growth rate increases (fiber strength decreases) the higher the tension, temperature, and presence of moisture.
    - Carbon coating reduces initial strength but prevents moisture ingress
- Hydrogen darkening
  - Pure silica core and/or carbon coating
- Thermal expansion of metals ($\alpha_{316L} = 16.2 \, \mu\epsilon/C^\circ$) vs. optical fiber ($\alpha_f = 0.5 \, \mu\epsilon/C^\circ$)
  - Extra Fiber Length
    - Implies fiber is free to move in cable, concept is incompatible with 1:1 strain coupling
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Typical Downhole Cable In Fiber-Instrumented Wells

- Designed to minimize risk of fiber failure (i.e., fiber break, high attenuation on fiber)
- Sepigel acts as hydrogen scavenger (eventually saturates)
- Holds multiple fibers (2 to 4, most commonly) (multimode and/or singlemode fibers)
- Historical initial applications:
  > optical link to downhole pressure/temperatures gauges (PDGs)
  > Distributed Temperature Sensing (DTS)
- Same cables used today for most crosswell strain monitoring over permanent fiber
## Instruments for Distributed Sensing of Strain

<table>
<thead>
<tr>
<th>Manufacturer</th>
<th>Halliburton</th>
<th>Lios (Luna)</th>
<th>Luna</th>
<th>Luna</th>
<th>Neubrex</th>
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<tbody>
<tr>
<td>Model</td>
<td>CRI-4400</td>
<td>OTS4</td>
<td>OBR4600</td>
<td>ODiSI 6100</td>
<td>NBX-SR7000</td>
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<tr>
<td>Technology</td>
<td>Pulsed Rayleigh</td>
<td>Brillouin OTDR</td>
<td>OFDR Rayleigh</td>
<td>OFDR Rayleigh</td>
<td>Pulsed/Frequency Sweep Rayleigh</td>
</tr>
<tr>
<td>Min Gauge Length</td>
<td>2.5 m</td>
<td>1.0 m</td>
<td>0.32 mm</td>
<td>0.65 mm</td>
<td>20 cm</td>
</tr>
<tr>
<td>Spatial Sampling</td>
<td>1.0 m</td>
<td>0.25 m</td>
<td>10 μm</td>
<td>0.65 mm</td>
<td>5 cm</td>
</tr>
<tr>
<td>Strain Resolution</td>
<td>0.01 με</td>
<td>2 με</td>
<td>1 με</td>
<td>1 με</td>
<td>1 με</td>
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<tr>
<td>Sample Period</td>
<td>$10^{-4}$ s</td>
<td>120 s</td>
<td>15 s</td>
<td>0.004 s</td>
<td>6s to 5min</td>
</tr>
<tr>
<td>Max. Fiber Length</td>
<td>10 km</td>
<td>30 km</td>
<td>70 m</td>
<td>100 m</td>
<td>27 km</td>
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<tr>
<td>Interrupt-Immune</td>
<td>No</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
<td>Yes</td>
</tr>
<tr>
<td>Absolute or Relative</td>
<td>Relative</td>
<td>Absolute</td>
<td>Relative</td>
<td>Relative</td>
<td>Relative</td>
</tr>
<tr>
<td>Reference for Calculating Strain</td>
<td>Previous scan (delta Phase)</td>
<td>Fiber $\nu_B(\lambda)$</td>
<td>Initial (or later) scan</td>
<td>Initial (or later) scan</td>
<td>Initial (or later) scan</td>
</tr>
<tr>
<td>Temperature Cross-sensitivity</td>
<td>$1^\circ C = 10 \mu\varepsilon$</td>
<td>$1^\circ C = 20 \mu\varepsilon$</td>
<td>$1^\circ C = 10 \mu\varepsilon$</td>
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</tr>
</tbody>
</table>
Lab Measurements Using OFDR
(Short Cable)
OFDR – Operating Principle

Frequency sweep of an interferometer

Frequency sweep interferometric interrogation of a sensing path
Principle of Distributed Acoustic Sensing (single-pulse)

Pulse of Narrow Linewidth (long coherence length) Laser Light

\[ \lambda_1 \]

10 ns

Optical circulator

Optical amplifier

Photo-detector

Electronic amplifier

Rayleigh Scattering

Rayleigh backscattering (≈-80dB/m)

Single-mode fiber 9 µm core

Detected Light Intensity (linear scale)

10 µs for \( L = 1 \text{km} \)

1m for \( \tau = 10 \text{ ns} \)
Frequency Shift Rayleigh Fundamental Working Principle

- **Pulse of Narrow Linewidth (long coherence length) Laser Light**
- **Optical circulator**
- **Optical amplifier**
- **Photo-detector**
- **Electronic amplifier**

Rayleigh Scattering

- Rayleigh backscattering ($\approx -80$ dB/m)

Single-mode fiber 9 $\mu$m core

- Different pattern observed with $\lambda_1$ due to added strain

10 $\mu$s for $L = 1$ km
Frequency Shift Rayleigh Fundamental Working Principle

- Pattern is recovered by using a longer wavelength
- Achieved by post-processing of OFDR scan (cross-correlated to baseline OFDR scan)

\[ \varepsilon_{opt}(z_i) = \frac{\lambda_2 - \lambda_1}{\lambda_1} = \frac{\Delta \lambda}{\lambda_1} \]

\( \Delta \lambda = \lambda_2 - \lambda_1 \)
Sample Configuration (Four Point Bending)

$\varepsilon_{defl} = \frac{12 \ y_{defl} \ v}{(L - B)(L + 2B)}$

All cables are glued to beam using JB Weld epoxy
Fiber Layout
(polyimide A→B, polyimide B→A,
New Cable 1 A→B, New Cable 2 B→A,
Sepigel A→B, Sepigel B→A)

Polyimide (glued to beam)
New Cables 1&2
FIMT+Sepigel (acrylate-coated fiber)
About the test sample

- Test was conducted to test New Cable test pieces #1 & #2
  - Working with a partner cable company. Not yet commercial. Results to be shared later.
- Polyimide-coated optical fiber bonded directly to beam (using JB Weld epoxy) is used as a 1:1 strain reference for the beam.
- FIMT+Sepigel was included for comparison. Decision had to be made about the boundary conditions:
  1. Leave fiber free to move at ends of FIMT
  2. Bond/crimp tube over fiber at ends of FIMT
- Since in a real gel-filled cable, the optical fiber at a strain concentration is able to “pull” fiber from above and below, we chose Option 1.
- Only profiles of Polyimide-coated fiber and FIMT+Sepigel are shared here.
Test Set-Up
Test Set-Up
Baseline Acquisition, Room Temperature

- Total fiber length = 21.559m
- Some loss of symmetry in the strain profile due to FIMTs coming outside of oven.
- Fibers in FIMT+Sepigel tension is limited due to fact that fiber is not restrained at the ends of the FIMTs.
Reference Fiber (Polyimide-coated)

Constant Temperature
Varying Deflection

\[ \varepsilon_{\text{defl}} = 407 \, \mu \varepsilon \]

\[ \varepsilon_{\text{defl}} = 109 \, \mu \varepsilon \]

109 \, \mu \varepsilon
217 \, \mu \varepsilon
328 \, \mu \varepsilon
435 \, \mu \varepsilon

T=23^\circ C

T=75^\circ C

150^\circ C

Constant Deflection
Changing Temperature
Drift Test: @125°C

Max Gradient Supported by the Sepigel at 125°C = 50 με/m. (50,000 με/km)
Implications of Results with FIMT+Sepigel Cable

- Standard cable using gel-filled FIMT were not intended for strain sensing
- However, cable can be used for cross-well strain monitoring due to:
  - Small strain amplitudes and small strain gradients
  - Data used for analysis is primarily strain rate, not absolute strain
- For long term strain monitoring applications, a designed-for-purpose strain sensing cable should be used.
Field Measurements Using Brillouin (Long Cable)
Monitoring Deployment of Disposable Fiber Using Brillouin

Effects of Temperature and Pressure are removed based on these assumptions:

1. Temperature profile is linear with True Vertical Depth (TVD)
2. Pressure gradient is linear with TVD
3. Zero tension at the tool location
Failure of Downhole Cable Cemented Behind Casing (Cable break, entry of fluid, tension in optical fiber)

Compression of Fiber due to Effect of Fluid Pressure on Sepigel (Compaction of Sepigel)

These are likely zones of fiber “take up” (underestimating the length of the compression zones.)

Relative Strain Profiles Obtained Using Brillouin Optical Time-Domain Reflectometry (Lios OTS4)
Concluding Remarks

- Optical fibers are sensitive to strain, temperature and pressure changes
  - Opportunities for new measurements (e.g., geomechanics)
  - Challenges in separation of the measurands

- Standard downhole cables were not intended for strain sensing
  - Suitable for cross-well strain (small strain gradients and strain magnitudes, limited duration)
  - Better strain cables needed to extend applications

- OFDR strain sensing instruments are great tools for lab characterization of cables
  - However, caution is needed in designing lab tests and in result interpretation
  - Easy to fall into traps in scaling results from lab to field
Acknowledgements

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THANK YOU

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