Distributed Wireless Antenna Sensors for Boiler Condition Monitoring

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Outline

- Project overview
- Past achievements
- Current achievements
  - Simultaneous strain and temperature sensing using a single patch antenna
  - High temperature sensor fabrication using alumina and platinum paste
  - Wireless UWB Tx/Rx antenna design for high temperature material and validation on PCB
  - Thermo-mechanical fixture design and evaluation
- Summary & conclusions
- Future work
- Q&A
**Project Overview**

Realize distributed condition monitoring of steam pipes up to 1000°C

- Wirelessly interrogate antenna sensors without electronics
- Characterize antenna sensors for temperature, strain, and soot accumulation
- Fabricate antenna sensors using high-temperature materials
Dual-Frequency Patch Antenna

\[ f_{mn} = \frac{C}{2\pi \sqrt{\varepsilon_{\text{reff}}}} \sqrt{\left( \frac{m\pi}{L_e} \right)^2 + \left( \frac{n\pi}{W_e} \right)^2} \]
Temperature-strain Differentiation

\[ f_{10} = \frac{c}{2\sqrt{\varepsilon_{\text{eff}} L}} \]

\[ \frac{\delta f_{10}}{f_{10}} = \frac{1}{2} \frac{\delta \varepsilon_{\text{eff}}}{\varepsilon_{\text{eff}}} \frac{\delta L}{L} \]

\[ \frac{\delta f_{01}}{f_{01}} = K_{TW} \Delta T + K_{W} \varepsilon_{L} \]

\[ \begin{pmatrix} \Delta T \\ \varepsilon_{L} \end{pmatrix} = \begin{bmatrix} K_{TL} & K_{L} \\ K_{TW} & K_{W} \end{bmatrix}^{-1} \begin{pmatrix} \delta f_{10}/f_{10} \\ \delta f_{01}/f_{01} \end{pmatrix} \]
Past Achievements
Wireless Interrogation - VNA

Antenna-sensor resonant frequency

\[ y = 195.13x + 1003.3 \]

\[ R^2 = 0.9984 \]

Wireless Interrogation – FMCW Radar

![Graph of Freq. and Amplitude vs. Temperature]

- For 25°C: $y = 186.36x + 1030.4$, $R^2 = 0.9961$
- For 50°C: $y = 193.45x - 608.05$, $R^2 = 0.9941$

$\Delta f_{\text{res}} / f_{\text{res}}$ (ppm) vs. Temperature Change $\delta T$ (°C)

- VNA
- FMCW
Single Antenna for Strain & Temp. Sensing

Furnace operation range: 280°C
Maximum load: 10 kN
Simultaneous Strain & Temp. Sensing

Excellent linearity: $R^2 = 0.9991$ for TM10 and 0.9995 for TM01

\[
\begin{bmatrix}
\frac{\delta f_{10}}{f_{10}} \\
\frac{\delta f_{01}}{f_{01}}
\end{bmatrix}
= \begin{bmatrix}
37.43 & -0.6861 \\
40.49 & 0.4302
\end{bmatrix}
\begin{bmatrix}
\Delta T \\
\varepsilon_L
\end{bmatrix}
\]

- Temperature error: $\pm 0.4^\circ C$
- Strain error: $\pm 17.22 \mu e$

Tchafa F. and Huang H., *IOP Smart Mater. & Struct.*, accepted 04/2018
Progress #1: Characterize Text Fixture for Strain and Temperature Loading Inside an Oven
Previous approach: generate mechanical strain with temperature change due to CTE mismatch between base plate and fixture

What we figured out

- Strain gages posses a thermal output – reference needed to extract mechanical strain
- Mfg. correction curve not suitable as it is affected by bonding as well base material
High-Temp Thermo-Mechanical Fixture

- Decouple strain and temperature
  - Strain is generated by weight
  - Temperature controlled by furnace

- Design constraints
  - Furnace dimensions
  - Substrate tensile properties
  - Strain resolution
  - Uniaxial loading

- Limitations
  - Limited strain generation based on substrate properties and size of weights
  - Need substrate with equal CTE along x- and y-directions to avoid bending of specimen
Fixture Characterization Outside of Oven

- DAQ
- Test fixture
- VNA
- Sensor
- Cable to VNA
- Applied weight
Measured Poisson’s ratio: 0.43 – good agreement with literature (0.4)

Excellent linearity: $R^2 = 0.9886$ and 0.9905 for the loading and transverse direction respectively

Measurement error: ± 9 microstrain
Progress #2: Fabricate Antenna Sensor Using High-Temperature Materials
Sensor Fabrication Using Alumina + Pt Paste

- Tape cast Pt paste on surface
- Curing process for 4 hours
- Substrate ultrasonic bath (cleaning process)
- Overnight drying of paste in oven
- Dry the paste and sinter Pt
  - 8 °C/min to 100 °C, 10 min hold, then 8 °C/min to 1000 °C, 10 min hold
- Remove mask if necessary
Surface Characterization

Challenges
- Uncontrollable platinum voids
- Other defects (no straight line edges)
- Difficult to achieve desired antenna shape
- Low gain

Proposed solutions
- Sensor fabrication with large offset
- Laser machining for razor-sharp edges
- Sensor redesign for performance improvement

Pattern thickness ~ 15 µm thick

Thickness increased near the edge (~0.18 mm wide)
High Temperature Antenna Sensor Design

Design of the antenna sensor using alumina and platinum

- Dimensions in (mm)
- Design dielectric: 9.8
- Substrate thickness: 1.2 mm
- Resonant frequency: ~3 GHz
- Time delay: 3.5 ns
Validating High-T Antenna Sensor Using PCB

- Substrate: Rogers 3010
- Thickness: 1.27 mm
Fabricate High Temperature Antenna Sensor

Before laser machining

After laser machining to obtain sharp edges
Resonant frequency: 2.95 GHz (good agreement with design frequency of 3 GHz)
- Measured gain: 3.3 dBi (major improvement from previous sensor gain of -9 dBi)
- Meandering line provides 3.5 ns delay
- Significant improvements in performance compared to previous design
Temp. Sensitivity of High-T Antenna Sensor

- Measurement error: ± 0.38°C
- Extracted TCDk: 127.5 ppm/°C
High-T UWB Antenna - Design

- Dimensions in (mm)
  - RIS ground: 4.9 x 4.9 mm² with 1.2 mm spacing
  - Substrate size: 49 mm x 55 mm

- 1.5 GHz bandwidth for both design using alumina and Pt

Simulated S11 parameters
UWB Antenna – PCB Implementation

Front

design 1
design 2

Back
PCB UWB Antenna - Characterization

- Broad bandwidth achieved for both designs
- Measured bandwidth: ~1 GHz
- Relatively flat gain in desired working range with mean gain of ~ 8dBi
Wireless interrogation distance: 0.6 m
Interrogation power: 10 dBm
Interrogating horn antenna gain: 12 dBi
Summary of Achievements

- Improved sensor fabrication process
  - Use laser machining to achieve precise dimensions and razor-sharp edges
  - Identified thickness variation issue through surface profiling

- High temperature sensor fabrication using high-temperature materials
  - Temperature sensitivity of 71.74 ppm/°C with measurement error of ±0.38°C
  - Extracted thermal coefficient of dielectric constant of 127.5 ppm/°C
  - Gain improvement through substrate thickness increase

- Thermo-mechanical fixture design and evaluation
  - Strain generated from applied weight and no longer from CTE mismatch
  - Limited to substrate with same CTE in both x- and y-direction to avoid bending

- Wireless UWB Tx/Rx antenna design on high temperature material
  - Design using alumina and Pt
  - Performance evaluation using commercial PCB
Publications


- Tchafa, F., and Huang, H., “Microstrip Patch Antenna for Simultaneous Strain and Temperature Sensing”, IOP Smart Mater. & Struct., accepted 04/2018
Future Work

- Demonstrate high-temperature wireless interrogation up to 1000°C
- Demonstrate high-temperature thermo-mechanical testing in fixture
- Implement antenna sensor array
- Investigate antenna sensor for soot detection
- Explore flexible & inexpensive high temperature materials
Question & Answers