Dielectric Spectroscopy for Sensing Fluid Power Contaminants

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Project Overview / Dielectric Spectroscopy for Sensing Fluid Power Contaminants

• Research goals:
  • Develop a dielectric sensor for on-vehicle real-time contamination detection.
  • Investigate the application of dielectric spectroscopy to
    • sensing particle contamination level in hydraulic fluid, and
    • detecting the presence of water or lubricating oil in compressed air.

• Relationship to CCEFP research strategy:
  • Addresses efficiency, miniaturization, ubiquity, and manufacturing goals

• Project’s original contribution:
  • Demonstrates potential of dielectric spectroscopy for contamination sensing

• Competing methods:
  • Particle counters

• Improvement over the competition:
  • Cost, Application to mobile platforms for real-time vehicle prognostics

Major Objectives/Deliverables

• Major objectives:
  • Demonstrate potential of dielectric spectroscopy for contaminant sensing
  • Develop a 1st generation prototype for vehicle based sensing
  • Explore design options with high-speed ADC/DACs

Next Steps

• Next 6 to 12 month plan:
  • Two journal articles in process
  • One conference paper
  • Secure additional funding

• How can industry help / contribute?
  • Engage in collaborative research

Funded by the NFPA Educational Foundation
Dielectric Spectroscopy

Frequency Response of Dielectric Mechanisms

Complex Relative Permittivity:

\[ \varepsilon_r = \varepsilon' - j\varepsilon'' \]

- \( \varepsilon' \) = Dielectric Constant (Energy Storage)
- \( \varepsilon'' \) = Loss Factor (Energy Loss)

\[ \varepsilon'' = \varepsilon_d + \frac{\sigma}{\omega \varepsilon_0} \]

Dielectric Loss

Conduction Loss

Capacitance of a Coaxial Capacitor

\[ C = \frac{2\pi \varepsilon_r \varepsilon_0 L}{\ln\left(\frac{b}{a}\right)} \]

Source – Agilent Technologies
Instrumentation principles

Material under test in sensor

Equivalent circuit:

Apply voltage and measure current:

Relate measurements to dielectric properties:

**Impedance:** $Z = \frac{V}{I}$

**Admittance:** $Y = \frac{1}{Z} = G + jB_c$

**Susceptance:** $B_c = 2\pi f C_o \varepsilon'$

**Conductance:** $G = 2\pi f C_o \varepsilon''$
Sensor Design

- Alignment pins
- Electrode and Shield assembly
- Adaptor for hydraulic tube connection
- Rod holder
- O-rings
Cutaway of the Sensor Assembly

Coaxial Electrodes

Passages For Electrical connections

Sensing Cavity Housing

Guard ring

Shielding tube

Insulating Layers

Flow

Flow
Hydraulic Test
Methods and Materials

- Two experiments performed with different contaminants:
  1) Iron powder (spherical, size <10μm in diameter; CAS #7439-89-6)
  2) ISO medium test dust (ISO 12103-1, A3 Medium, Silica 68-76% by mass)

- Shell Tellus ISO VG 46 hydraulic oil
- Constant temperature (34 degrees C)
- Oil flow rate - 350 ml/min (~ 0.1 gpm)
- Measured conductance and susceptance:
  - 3 Replications
  - 63 frequencies (5Hz – 13MHz)
- Sensor calibrated using ISO 4406 cleanliness code (range 14/12/10 to 24/22/20) using inline particle counter (MpFiltri ICM)
- Impedance measured with an Hp 4192 LF Impedance Analyzer
Hydraulic Test Circuit

- Oil Drum
- Clean Fluid Reservoir
- Pall 7 µm Filter
- Donaldson 7 µm Filter
- Dielectric Sensor
- Sample Port
- Temperature controlled hot bath
- Shut-off valve 1
- Shut-off valve 2
- Shut-off valve 3
- Shut-off valve 4
- Shut-off valve 5
- Reservoir for mixing contaminants
- Hydraulic Test Fluid
- Particle counter
- Check valve

Flow rates:
- 10.4L/min
- 0 to 1600 mL/min
- 0 to 3400 mL/min
PLS Regression for Iron Powder

Central rod diameter = 0.70 inch

RMSEC = 0.62
RMSECV = 0.83

Central rod diameter = 0.25 inch

RMSEC = 1.1
RMSECV = 1.39
PLS Regression for ISO Test Dust

RMSEC = 1.29
RMSECV = 1.48
## Experiments and Results

<table>
<thead>
<tr>
<th>Contaminant</th>
<th>Central Rod Diameter</th>
<th>Replications, Samples</th>
<th>RMSEC (Adjusted ISO Code)</th>
<th>RMSECV (Adjusted ISO Code)</th>
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</thead>
<tbody>
<tr>
<td>Iron Powder</td>
<td>0.25</td>
<td>2, 22</td>
<td>1.1</td>
<td>1.39</td>
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<tr>
<td>Iron Powder</td>
<td>0.70</td>
<td>3, 33</td>
<td>0.62</td>
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<td>3, 31</td>
<td>1.29</td>
<td>1.48</td>
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</table>
Contamination Sensing in a Compressed Air Stream

- Two experiments performed with different liquids:
  1) Deionized water
  2) Pneumatic lubricant Oil (Sunoco Sunvis 932)
- PVC Test Chamber: Volume for fluid droplet entrainment in air stream
- Industrial nozzle for atomization of water and lubricating test fluid
- Compressed air flow rate – 40 cfm
- Measured capacitance and dissipation factor
  - 3 Replications
  - Frequencies
    - 1MHz – 13MHz (Deionized water)
    - 100 kHz -13 MHz (light oil)
Mixing chamber

Airstream

Pressurized liquid

Air and Droplet Mixture to sensor
Hydraulic Circuit for Atomizing Test Fluids

Diaphragm pump → Pressure Relief Valve → Shut-off valve

Reservoir → Pressure Relief Valve

Nozzle
Pneumatics Test Stand

Compressed air inlet

Pressurized liquid inlet

Dielectric Sensor
Test Results

Standardized capacitance at multiple frequencies

Water

Oil

Data on a new hyperplane after rotation through PCA

Legend, Water
- No Spray, Training Set
- Spray, Training Set
- No Spray, Prediction Set
- Spray, Prediction Set

Legend, Oil
- No Spray, Training Set
- Spray, Training Set
- No Spray, Prediction Set
- Spray, Prediction Set
## Tests and Results

<table>
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<tr>
<th>Tests with</th>
<th>Replications, Total samples</th>
<th>Frequency Range</th>
<th>Cases</th>
<th>Samples</th>
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<td>No-spray</td>
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<td>100 kHz – 13 MHz</td>
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<tr>
<td></td>
<td></td>
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<td>No-spray</td>
<td>35</td>
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### Training Set

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<th>Actual</th>
<th>Predicted</th>
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### Test Set

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<td>Spray</td>
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### Light Lubricant Oil

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<tr>
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<table>
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<tr>
<td>Spray</td>
<td>0</td>
<td>12</td>
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</table>
Conclusions

• Dielectric spectroscopy:
  – Has good potential to detect particle contaminants in a flowing hydraulic fluid at levels that are consistent with modern hydraulic components.
  – can accurately detect the presence of liquid droplets in a compressed air-stream.
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