Microwave Interferometry for Metal Surface Displacement Detection Through Insulating Layers

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Background

Acoustic Energy

- Effective for inspecting metal parts.
- Traditional ultrasound inspection requires access to the entire metal part.
- Insulation (rubber, foam, etc.) is a poor sound conductor.
- Removing and re-applying insulation is often undesirable.

Metal objects coated in insulating material present inspection challenges.

Electromagnetic Energy

- Reflects strongly from metal surfaces.
- Readily penetrates insulating materials.
- Can be used as a ‘receiver’ for scattered acoustic waves.

We demonstrate a hybrid acoustic/electromagnetic inspection system.
Inspection technique

- Excite sample with acoustic pulse (requires single contact point).
- Map surface deflection with MI.
- Pulse propagation map yields locations of acoustic scatterers (flaws).
Microwave Interferometry – hardware overview

- Equipment used for these experiments:
  - 94 GHz interferometer
  - TI AD8347 Mixer
  - Stanford Research low noise pre-amplifiers
MI Principles of Operation – Round-trip Phase Change

- MI provides measurement of round-trip phase change/Doppler frequency:

  \[ \Delta l_\lambda = \frac{0.5*\Delta \phi}{2\pi} \]

  \[ \text{Path length change} \quad \Delta l_\lambda = \frac{0.5*\Delta \phi}{2\pi} \]

  \[ \text{Received signal is mixed with reference to obtain:} \]

  \[ r_e = A_2 \cos(\omega_h t + k_h (D + \delta(t))) \]

  \[ \text{Standoff distance} \quad \text{Surface displacement} \]

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- Received signal is mixed with reference to obtain:

  \[ \text{mix}_1 = A_1 A_2 \left[ \frac{1}{2} \cos(-k_h (D + \delta(t))) + \cos(2\omega_h t + k_h (D + \delta(t))) \right] \]

  \[ \text{Low freq.} \quad \text{High freq.} \]

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  - Surface displacement

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  - Low freq.
  - High freq.

MI Principles of Operation

- With the use of a mixer supplying in-phase and quadrature output:

\[
LF_1 = \frac{1}{2} A_1 A_2 \cos(k_h D) - \frac{1}{2} A_1 A_2 k_h \sin(k_h D) \delta(t)
\]

\[
LF_2 = -\frac{1}{2} A_1 A_2 \sin(k_h D) - \frac{1}{2} A_1 A_2 k_h \cos(k_h D) \delta(t)
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Experimental Configuration
Measurement Results

Microwave interferometer detects surface displacement of +/- 15 nm with and without rubber layer

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Measurement Results – Metal Shield

MI response not due to electrical cross-talk.
1D Measurements on 2D plate

Measurement locations

Comsol model
1D Measurements on 2D plate

Measurement locations

Comsol model

Increasing distance from shaker
Conclusions

- Microwave system successfully observes metal through insulator.
- Successfully detected surface deflection $2 \times 10^5$ times smaller than microwave wavelength.
- 1D scan indicates system can track acoustic pulse propagating in insulated metal plate.
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- Using angle sum identity:

\[
\cos(\alpha + \beta) = \sin(\alpha) \cos(\beta) + \cos(\alpha) \sin(\beta)
\]

- And small angle approximations:

\[
\begin{align*}
\cos(\delta(t)) & \approx 1 \\
\sin(\delta(t)) & \approx (\delta(t))
\end{align*}
\]

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- Quantitative displacement can be calculated:

\[
\delta(t) = \left(\frac{1}{k_h}\right) \frac{(DC_{mix1}) \cdot (AC_{mix2}) + (DC_{mix2}) \cdot (AC_{mix1})}{(DC_{mix1})^2 + (DC_{mix2})^2}
\]

- In practice, errors in the DC components make quantitative displacement difficult to measure.