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.

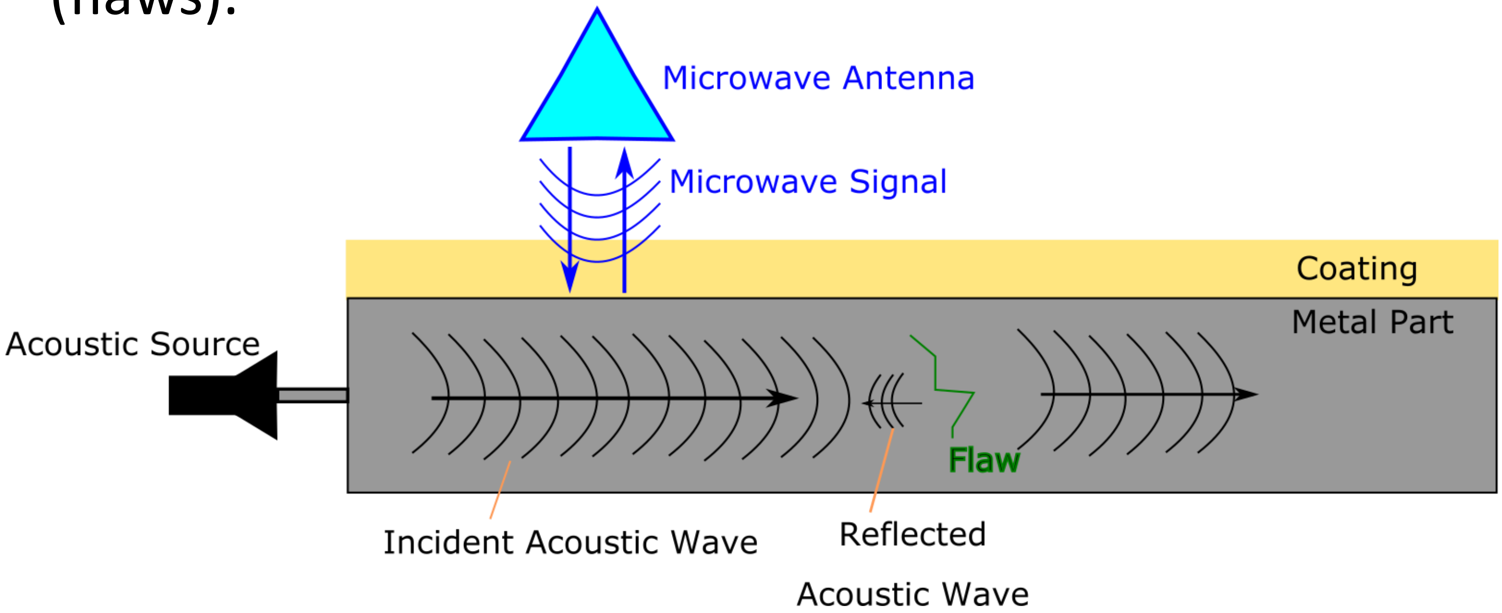
Electromagnetic Energy

- 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.

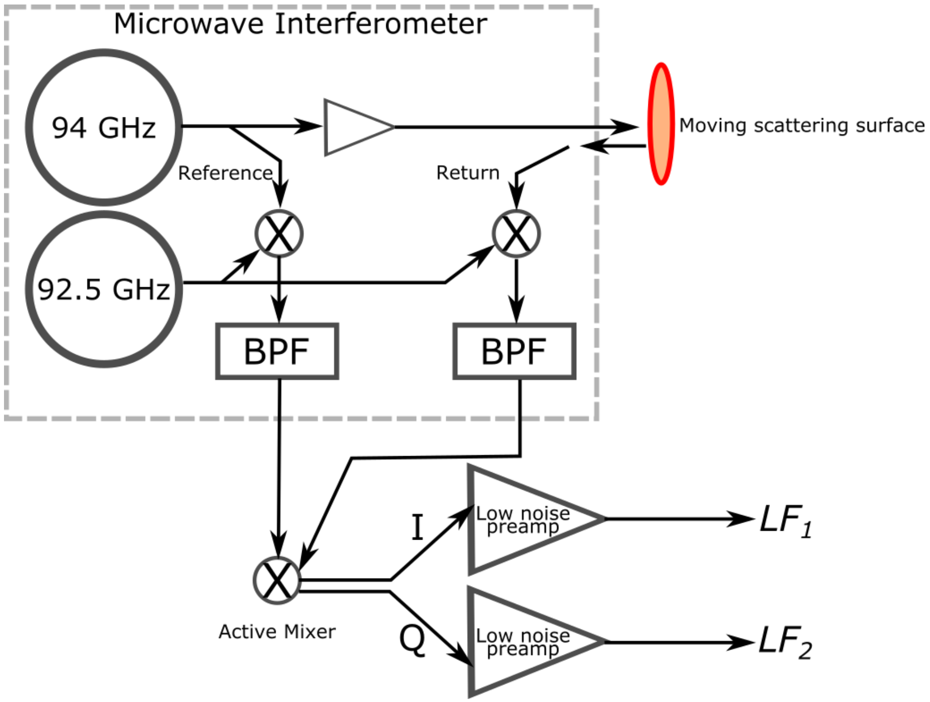
Inspection technique

- 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

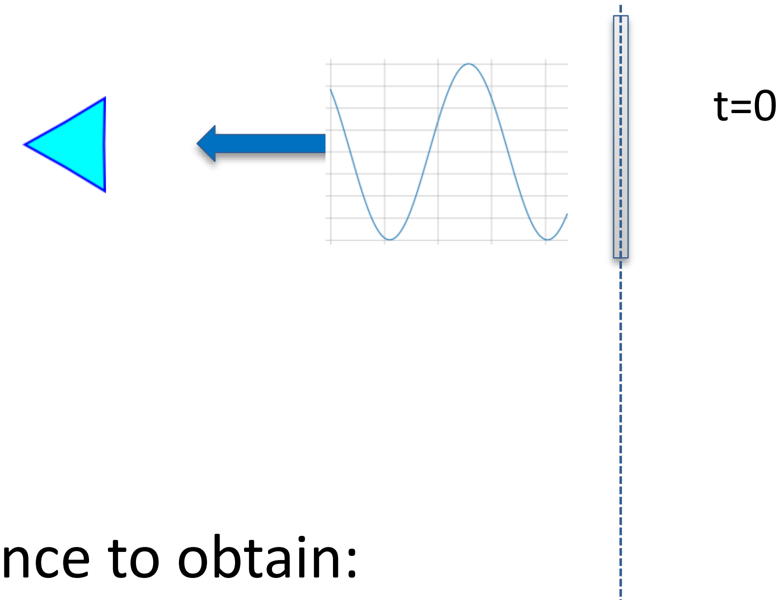
- Equipment used for these experiments:
  - 94 GHz interferometer
  - TI AD8347 Mixer
  - Stanford Research low noise pre-amplifiers



MI Principles of Operation – Round-trip Phase Change

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

Path length change $\Delta l_{\lambda} = \frac{0.5 * \Delta\phi}{2\pi}$



$$rec = A_2 \cos(\omega_h t + k_h (D + \delta(t)))$$

Standoff distance

Surface displacement

- Received signal is mixed with reference to obtain:

$$mix_1 = A_1 A_2 \left[\underbrace{\tfrac{1}{2}\cos(-k_h (D + \delta(t)))}_{\text{Low freq.}} + \underbrace{\cos(2\omega_h t + k_h (D + \delta(t)))}_{\text{High freq.}}\right]$$

Signal analysis follows J. S. Martin *et al.*, "Ultrasonic displacement sensor for the seismic detection of buried land mines," 2002, pp. 606–616.

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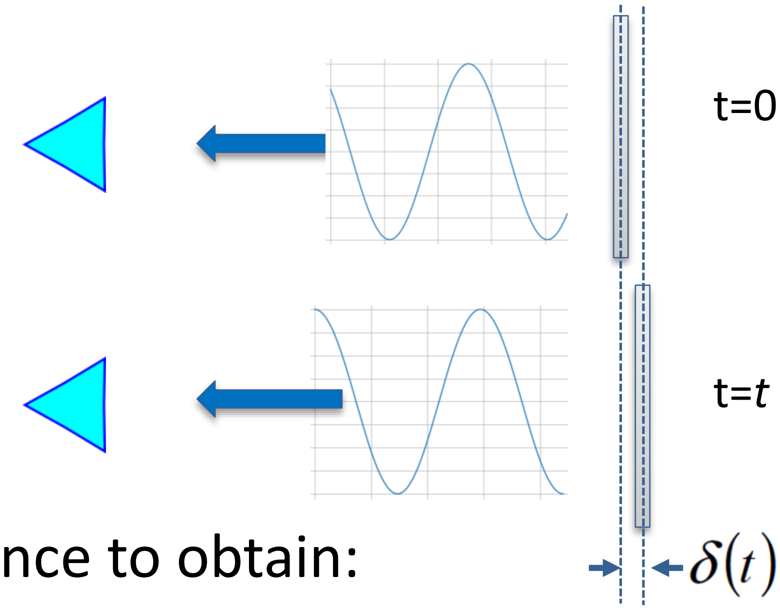

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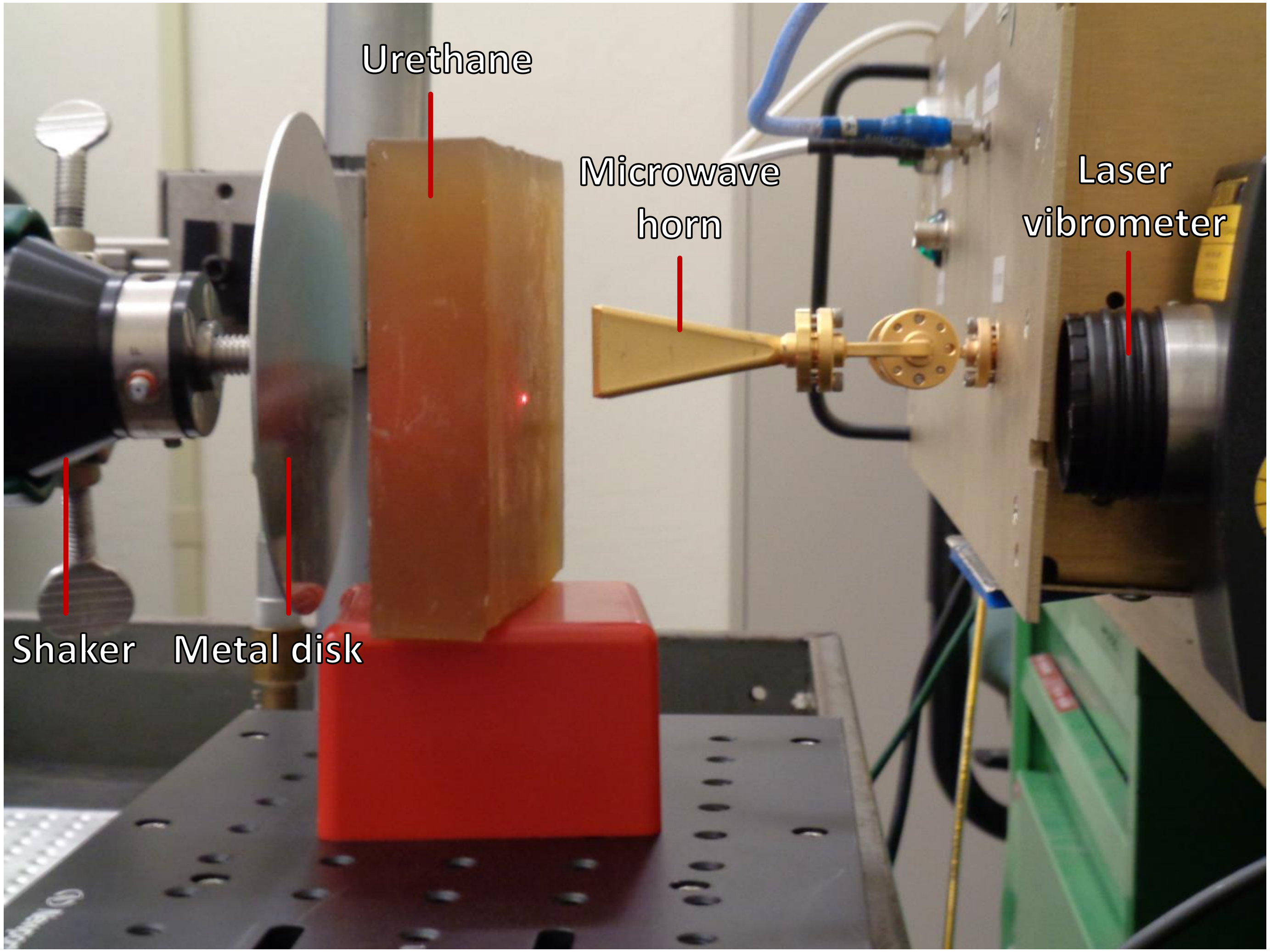
MI Principles of Operation

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

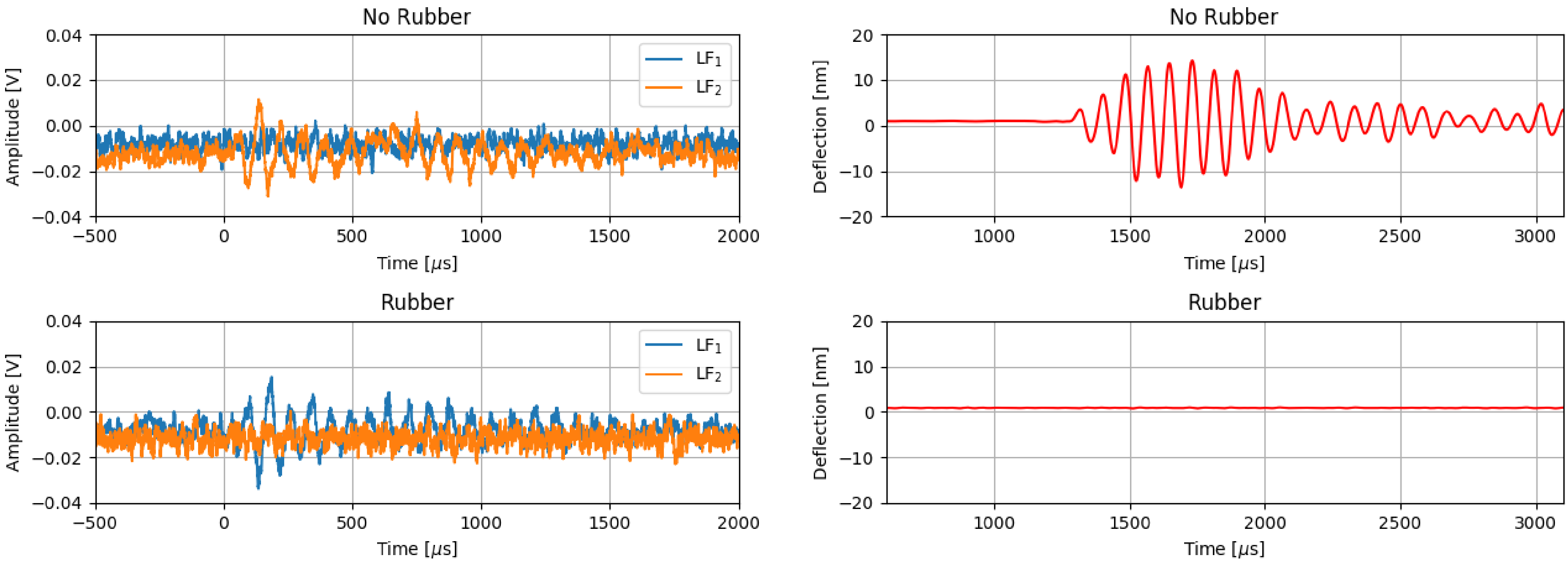
$$LF_1 = \tfrac{1}{2} A_1 A_2 \cos(k_h D) - \tfrac{1}{2} A_1 A_2 k_h \sin(k_h D)\delta(t)$$

$$LF_2 = -\tfrac{1}{2} A_1 A_2 \sin(k_h D) - \tfrac{1}{2} A_1 A_2 k_h \cos(k_h D)\delta(t)$$

Experimental Configuration



Measurement Results



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

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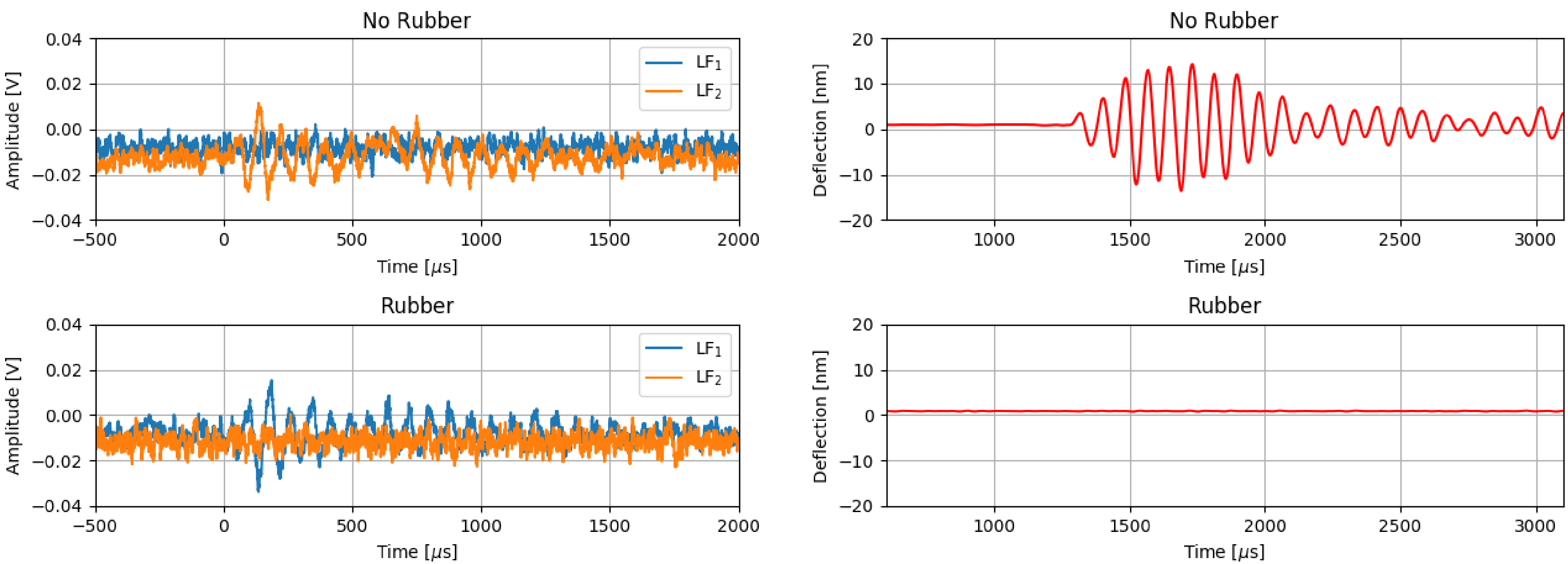

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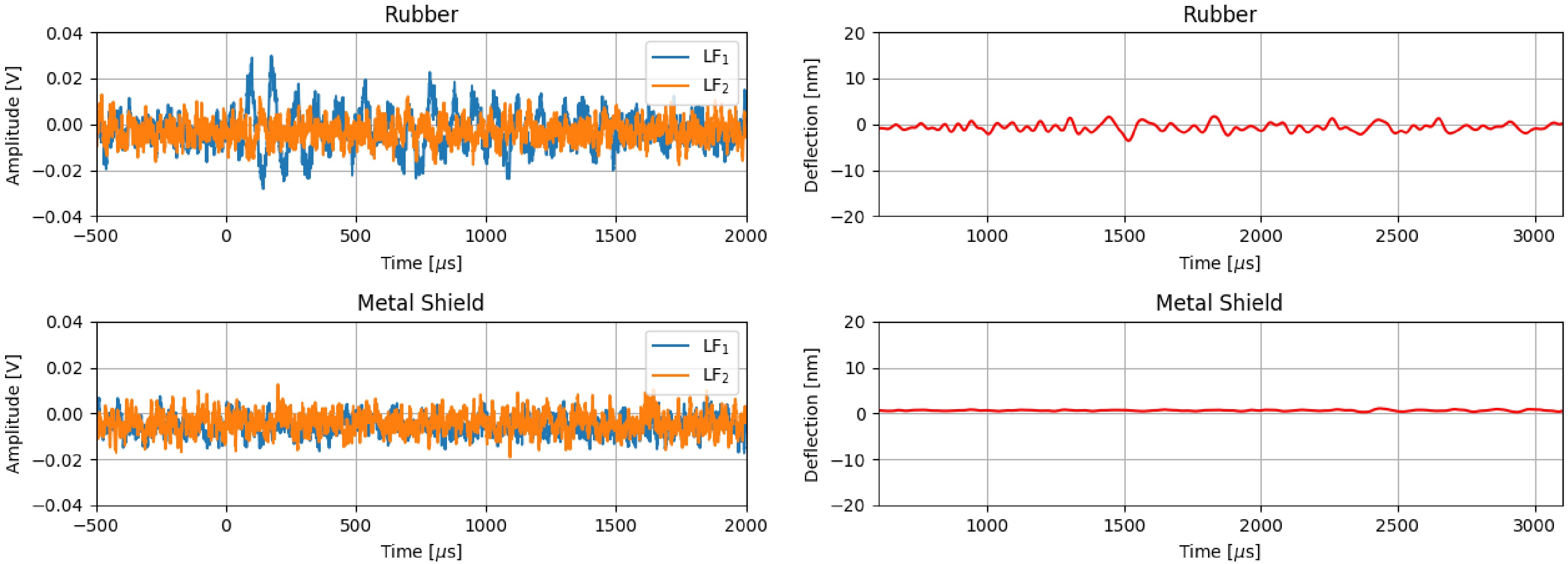
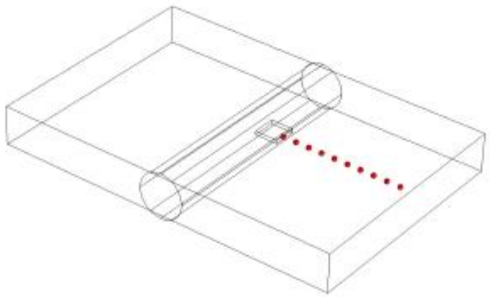
Measurement Results – Metal Shield



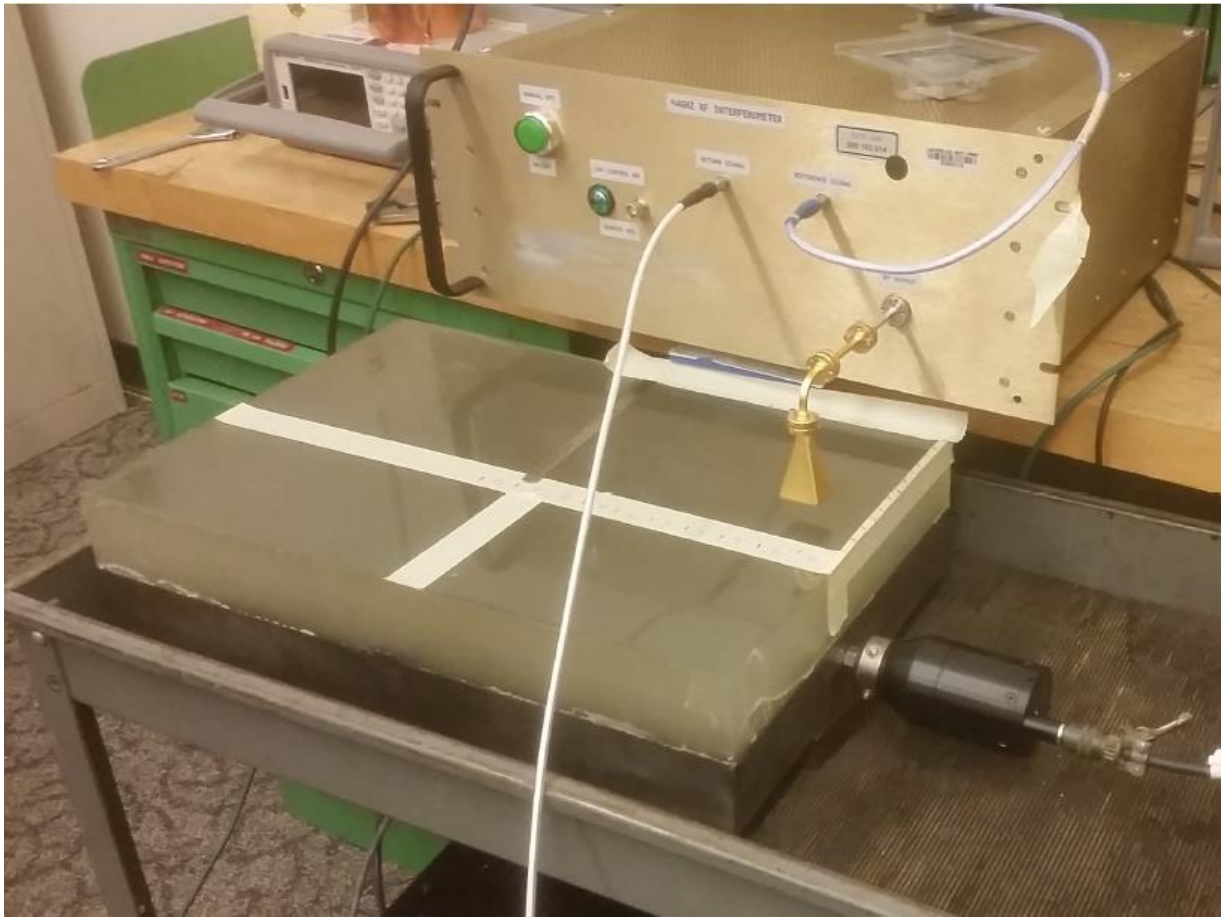
MI response not due to electrical cross-talk.

1D Measurements on 2D plate



Measurement locations

Comsol model



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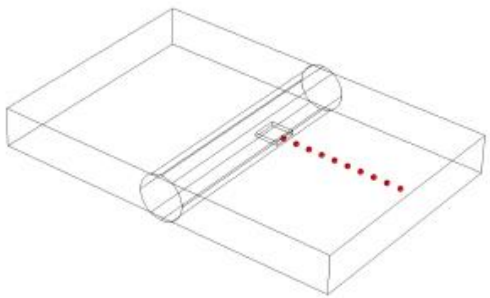

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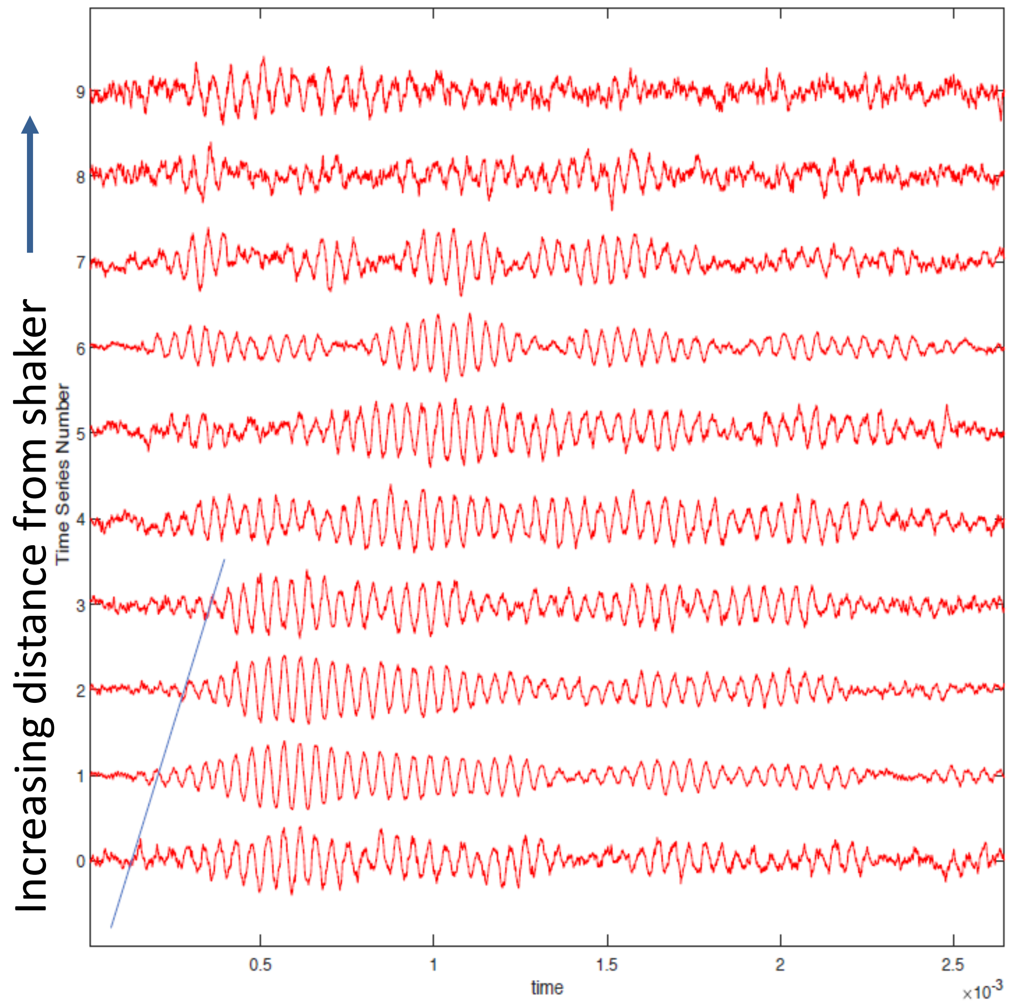

Conclusions

- Microwave system successfully observes metal through insulator.
- Successfully detected surface deflection $2x10^5$ times smaller than microwave wavelength.
- 1D scan indicates system can track acoustic pulse propagating in insulated metal plate.

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MI Principles of Operation

- Received signal is mixed with reference to obtain:

$$mix_1 = \boxed{A_1 A_2 [\tfrac{1}{2}\cos(-k_h(D+\delta(t)))} + \cos(2\omega_h t + k_h(D+\delta(t)))]$$

- Using angle sum identity:

$$\cos(\alpha+\beta) = \sin(\alpha)\cos(\beta) + \cos(\alpha)\sin(\beta)$$

- And small angle approximations:

$$\cos\big(\delta(t)\big) \approx 1$$
$$\sin\big(\delta(t)\big) \approx (\delta(t))$$

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

$$LF_1 = \tfrac{1}{2} A_1 A_2 \overbrace{\cos(k_h D)}^{DC_{mix1}} - \tfrac{1}{2} A_1 A_2 k_h \overbrace{\sin(k_h D)\delta(t)}^{AC_{mix1}}$$

$$LF_2 = -\tfrac{1}{2} A_1 A_2 \underbrace{\sin(k_h D)}_{DC_{mix2}} - \tfrac{1}{2} A_1 A_2 k_h \underbrace{\cos(k_h D)\delta(t)}_{AC_{mix2}}$$

- 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.