Second Harmonic Passive Thermography Generated by Cyclic Loading in Composites

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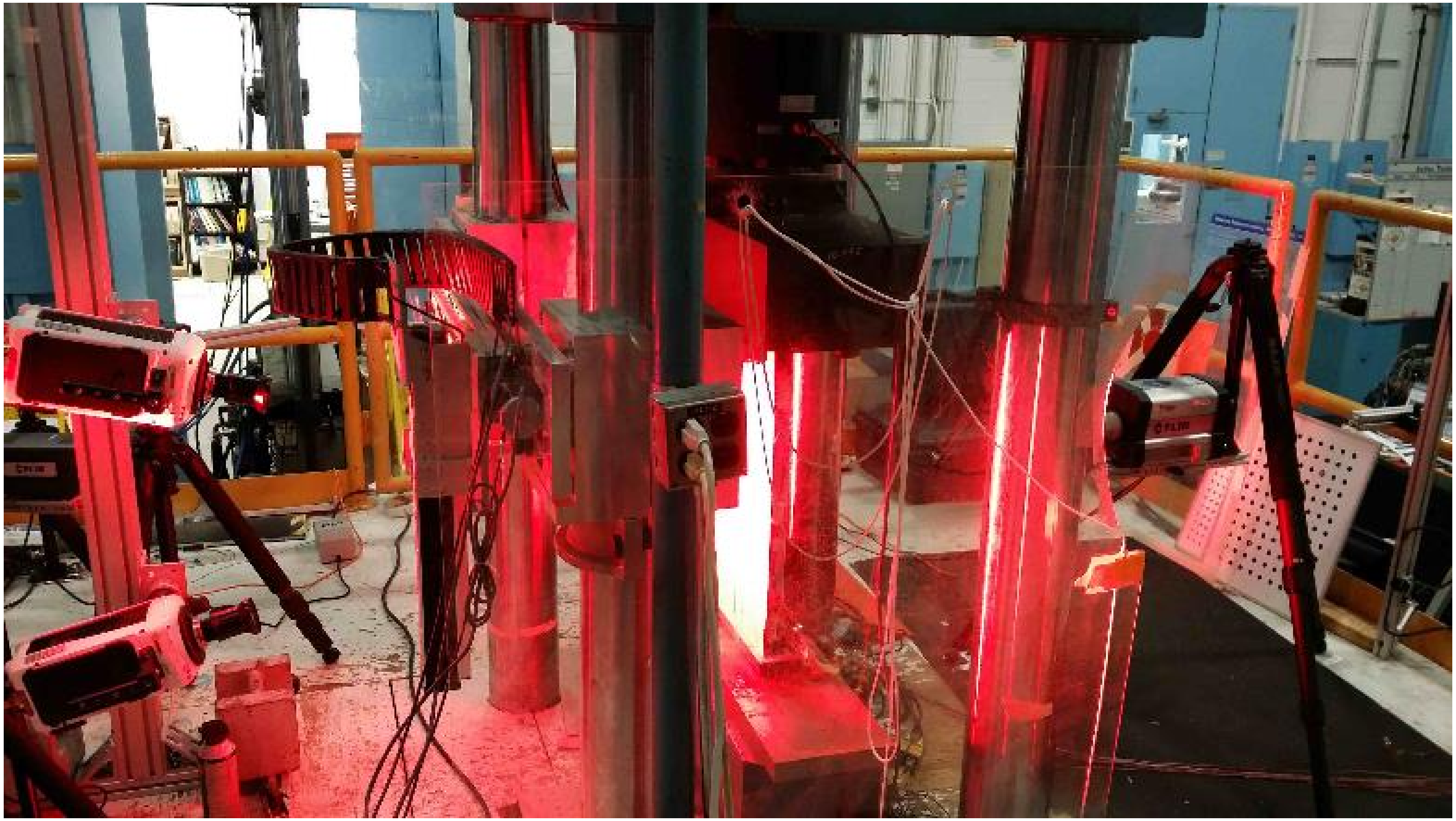
Outline

- Introduction
- Passive Thermography for In Situ Inspection
  - Identification of points with large harmonic content in thermal responses
- Modeling
  - Phase from Friction Heating
  - One Dimensional Series Solution
  - Two Dimensional Quadrupole Solution
- Comparison Model Output and Measurements
- Summary

Load Testing Configuration



Passive Thermography

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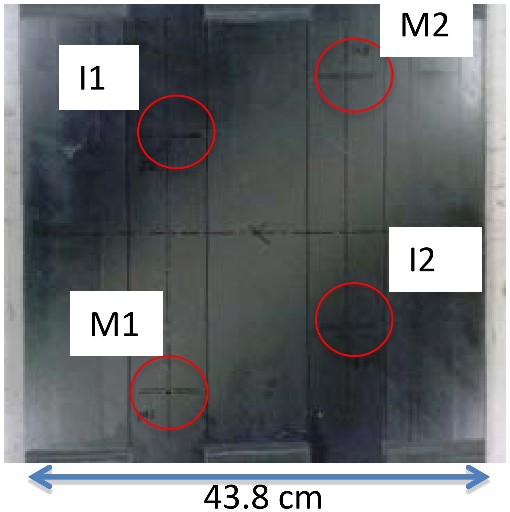
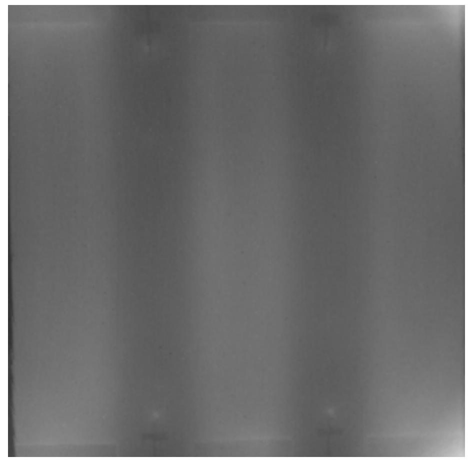
- Passive thermography provides wide area inspection of a composite structure during load testing to monitor damage growth and determine when to stop the fatigue loading.
- Most prior efforts have focused on responses that occurs at the same frequency as the cyclic loading
- At some points there is a significant signal at twice the frequency – the phase of these points fall in a relatively small range

Real Time Inspection Passive Thermography Raw Images

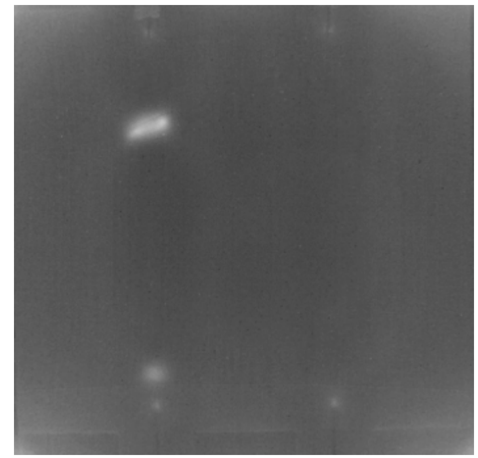
Flat Side



31.6% of Life



97.3% of Life



98.6% of Life

99.2% of Life

99.9% of Life

Thermal Responses from Flawed, Unflawed Regions and Points with Large Harmonics

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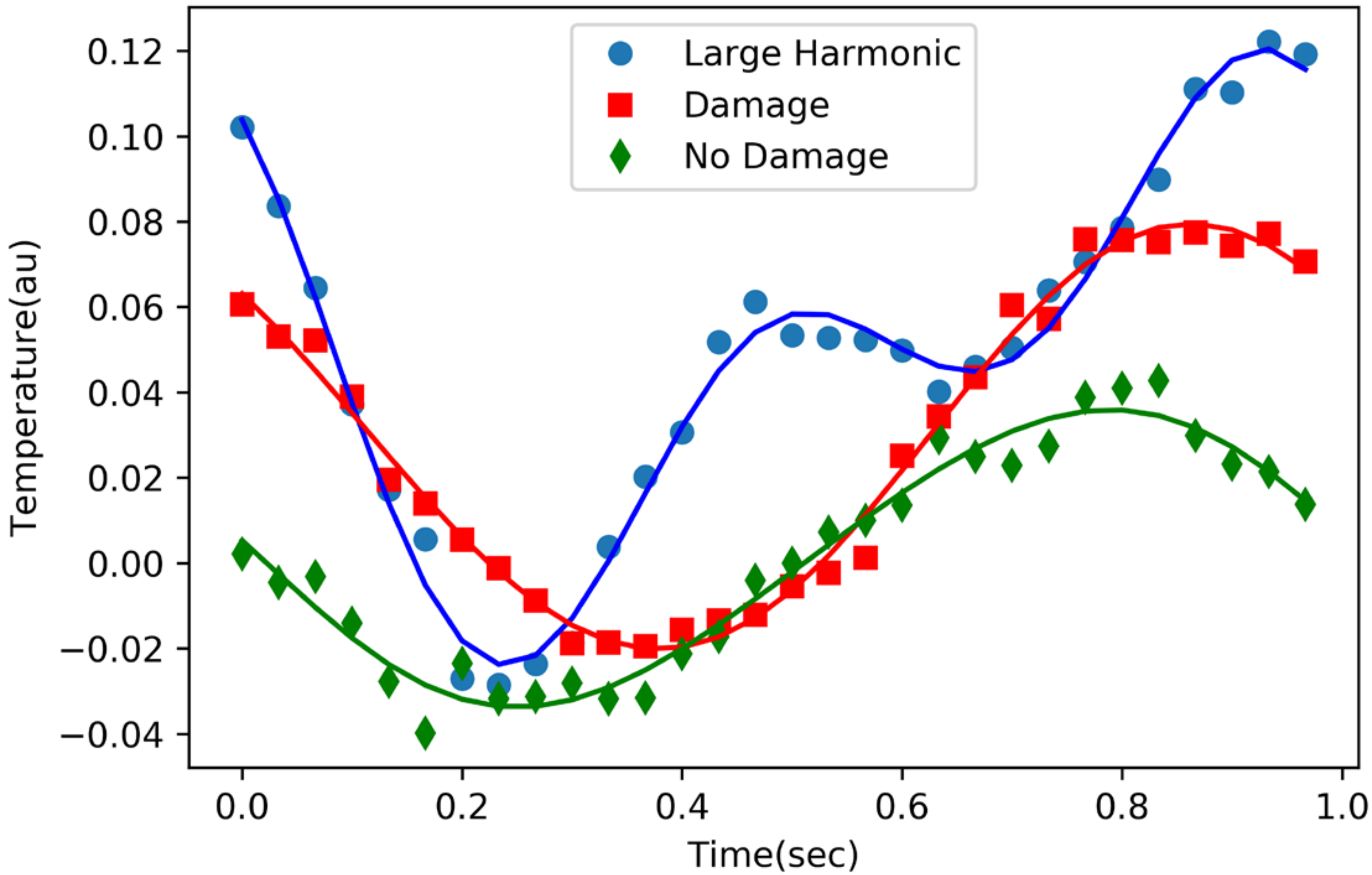


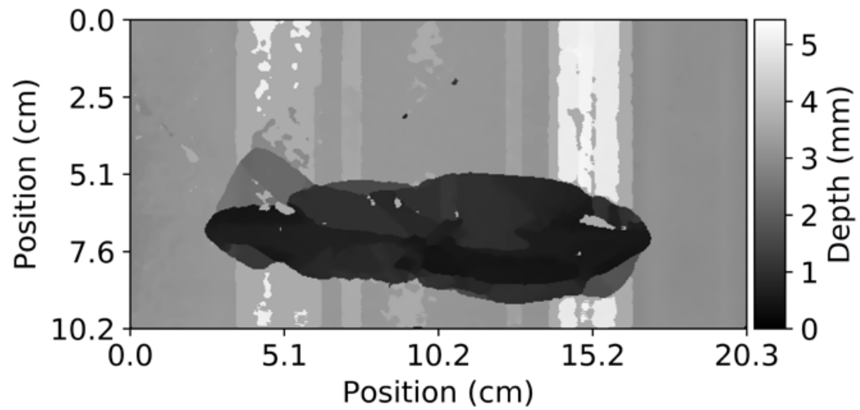
Solid Lines are fits of responses with:

$T(t)=a_0+a_1\,t + a_2\cos(\omega\,t) + a_3\sin(\omega\,t) + a_4\cos(2\,\omega\,t) + a_5\sin(2\,\omega\,t)$

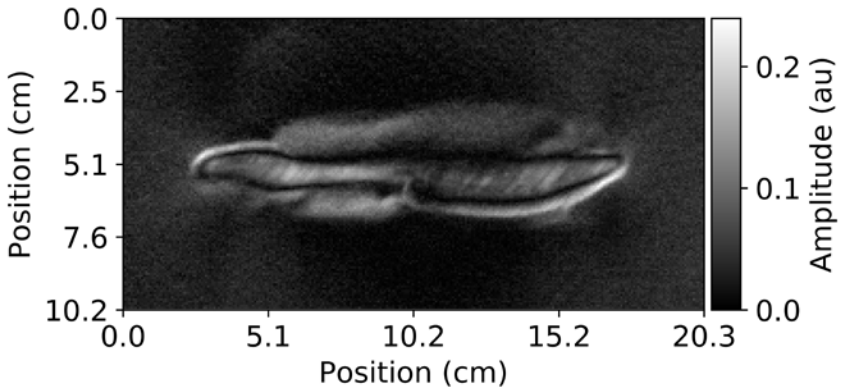
$\omega = 4\,\pi/\text{sec}$

UT Depth Map and Passive Thermography Maps

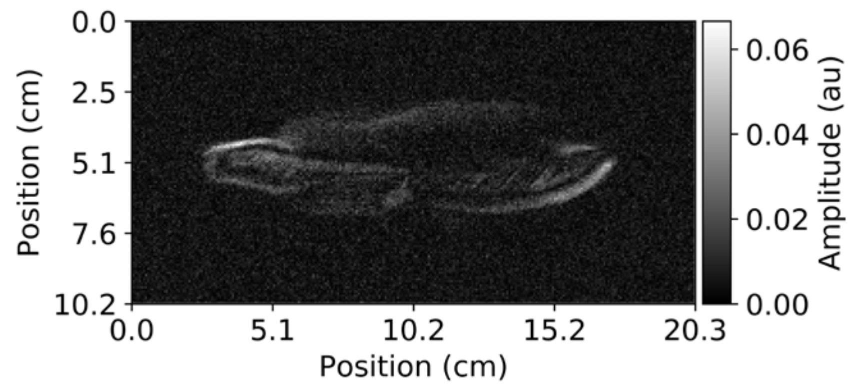
Depth of Damage from UT Measurement



Amplitude of Passive Thermography Fundamental

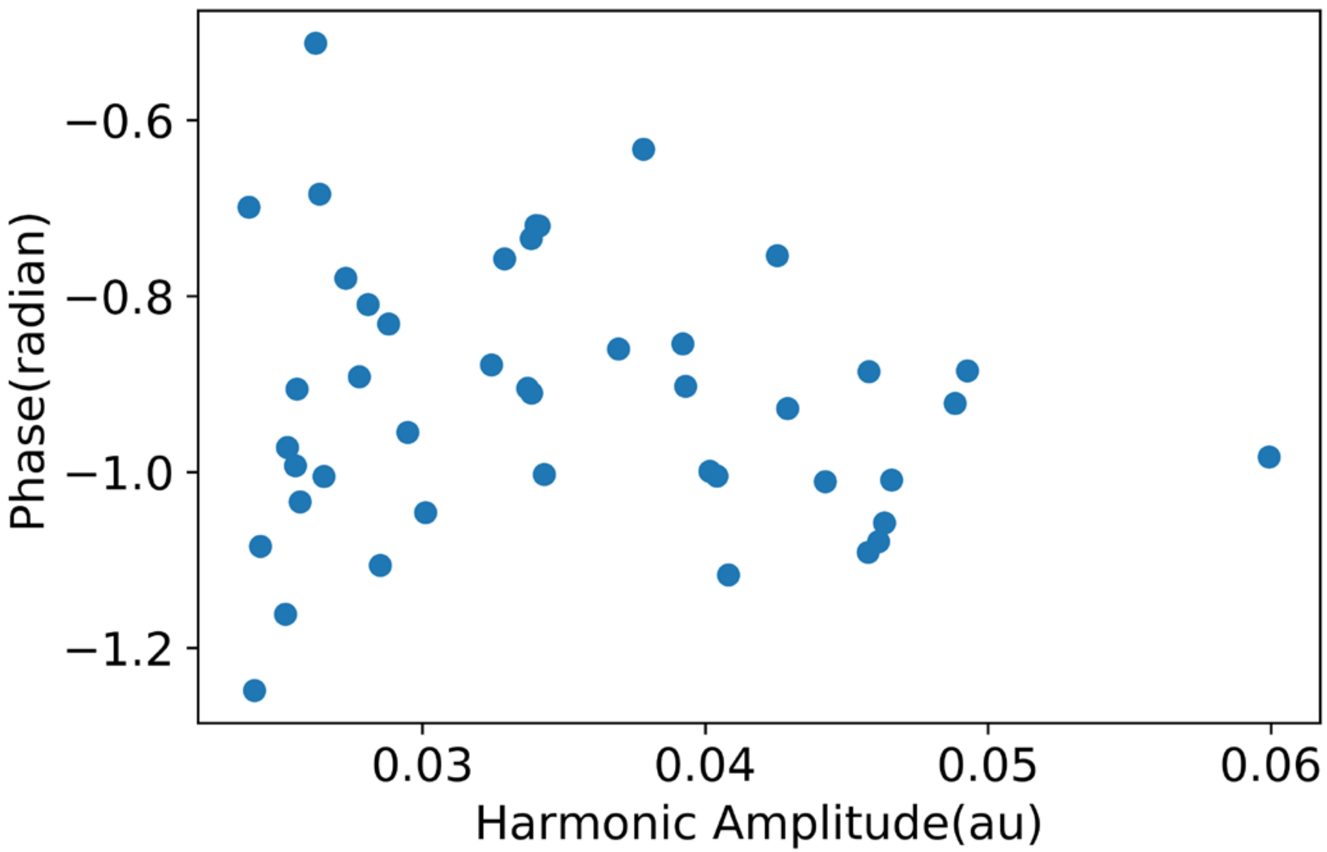


Amplitude of Passive Thermography Harmonic



Points with Largest Passive Thermography Harmonic Amplitudes

Phases for Large Amplitude Harmonic Responses

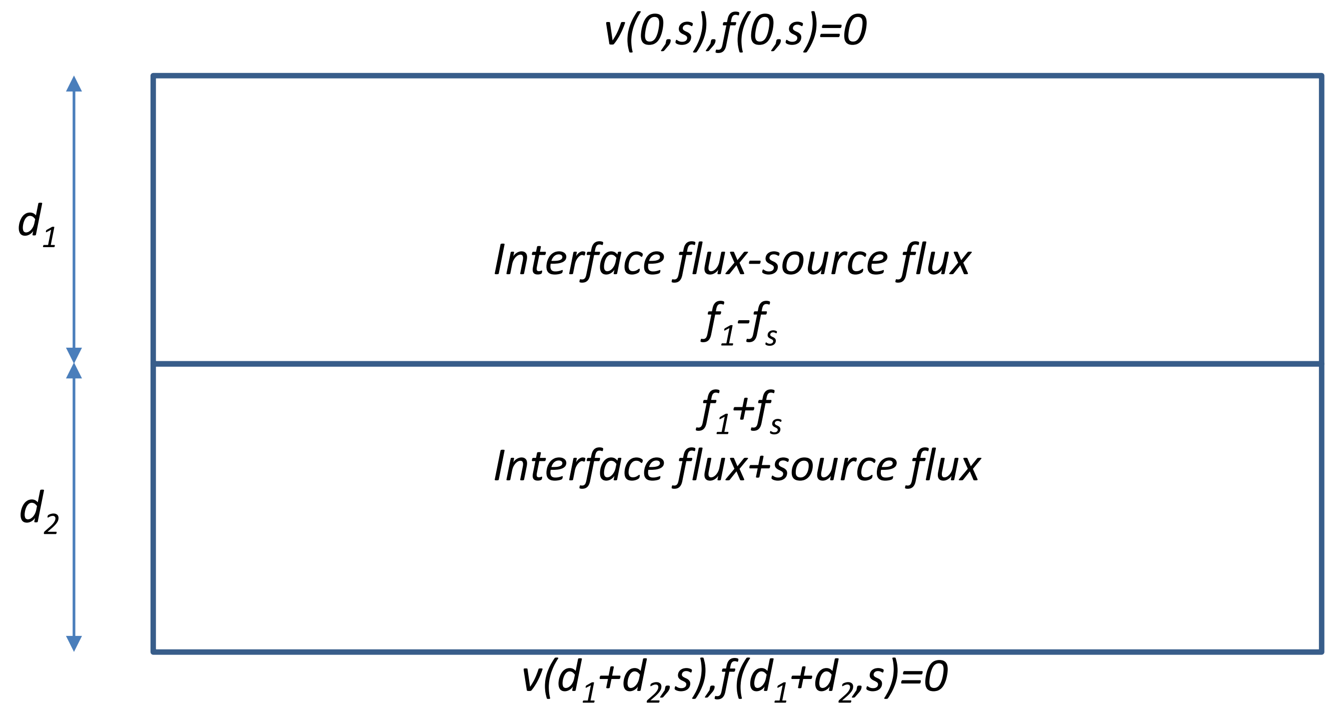


Average phase = -0.90 rad
Standard Deviation = 0.15 rad

Simple Friction Source

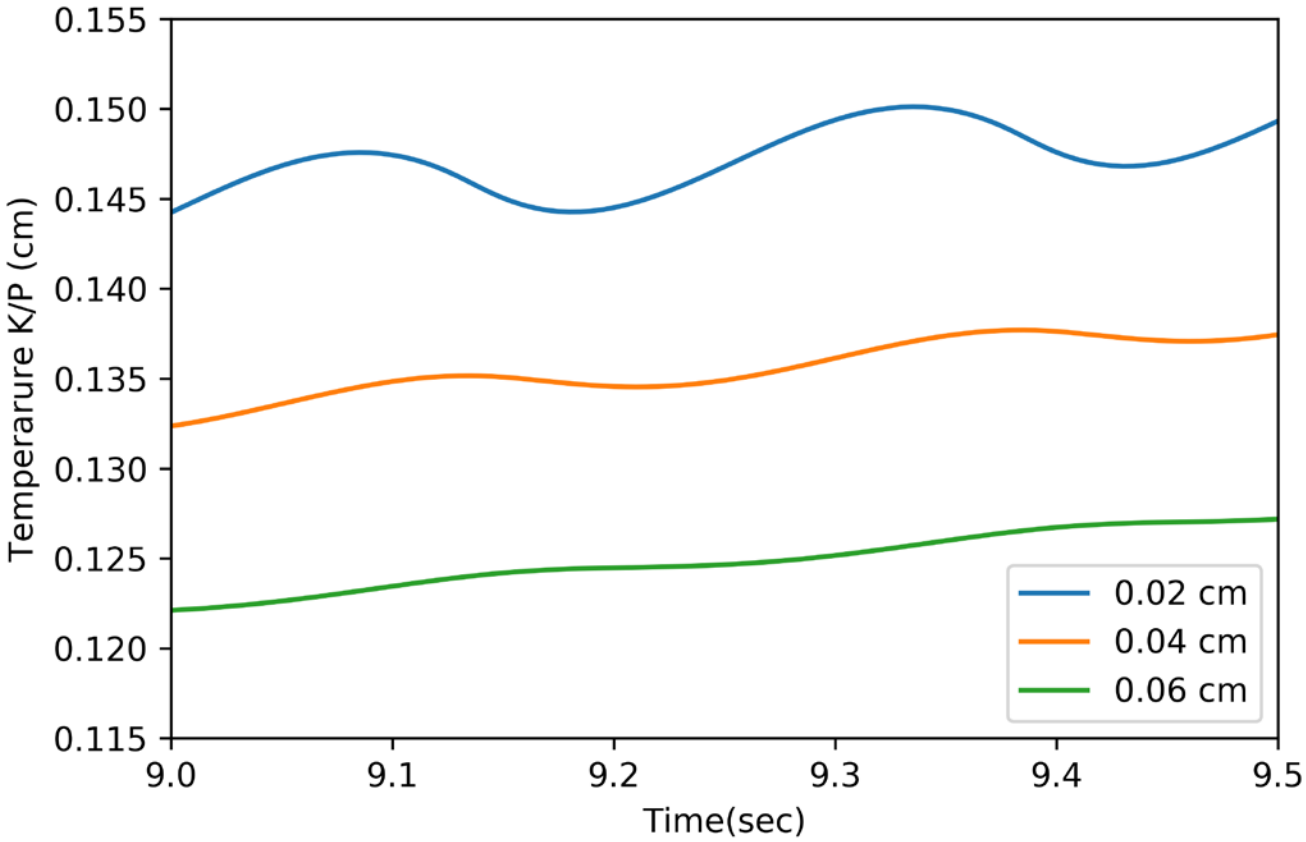
- Focus is determining the phase
- Power expended in moving object against force – $P = \overline{F} \bullet \overline{v}$ where v is the velocity
- v is relative movement of two surfaces of a delamination
- Assume amplitude of $\overline{F}$ is constant
- Relative displacement of surfaces is proportional to sin(ω t)
- Magnitude of velocity proportional to |cos(ω t)|
- Power proportional to |cos(ω t)|

One-Dimensional Model with Subsurface Source



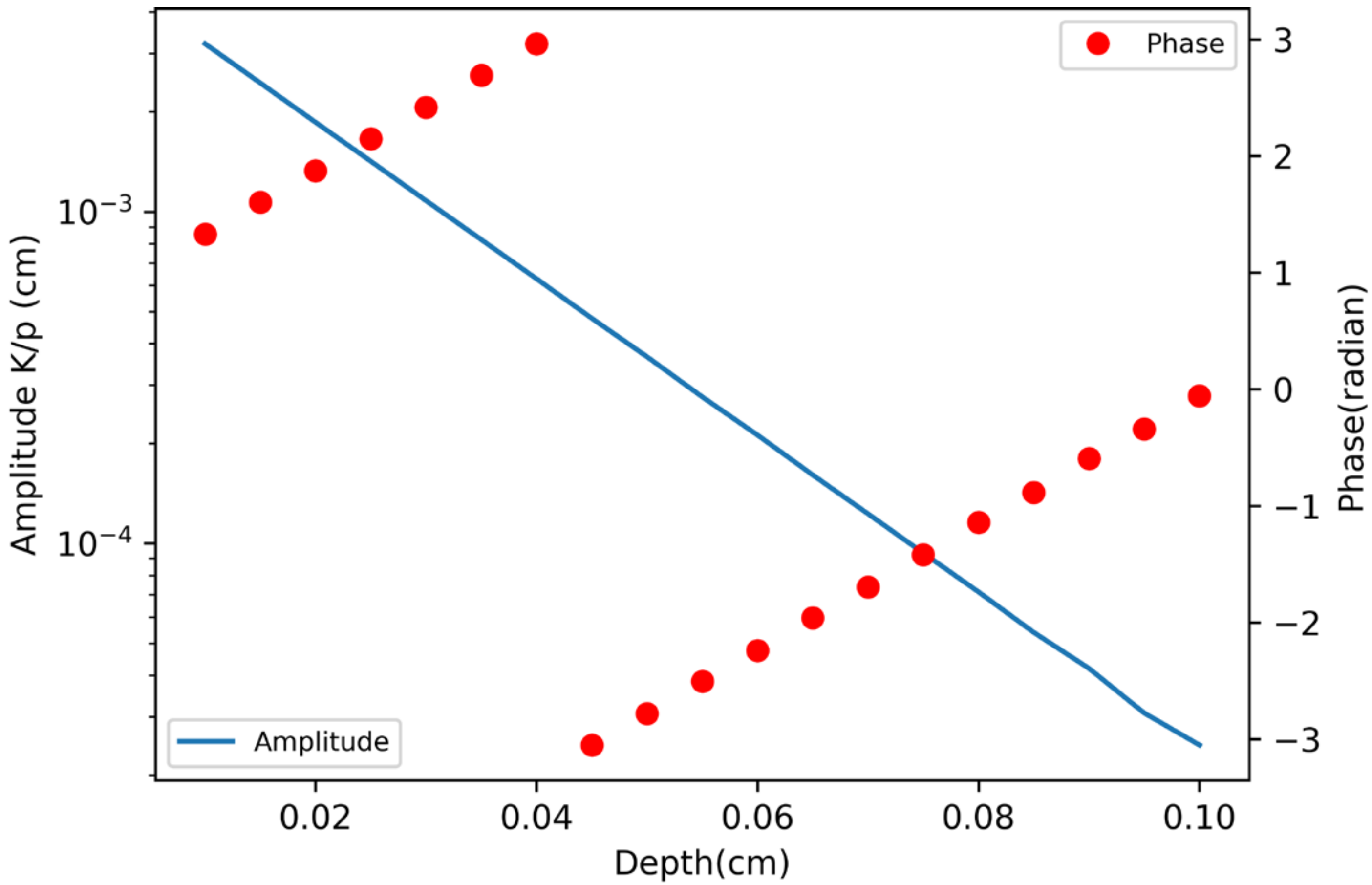
- Interface flux is the result of a temperature gradient at the interface and needs to be solved for
- Source flux, f_s, is from heat generated at the interface, $f_s = C|\cos(\omega t)|$
- Series solution is possible (details in paper)

Series Solution for P |cos(ω t)| Source at Different Depths Below Surface



Block thickness is 0.32 cm,
Diffusivity=0.00425 cm^2/sec, Frequency=2 Hz

Amplitude and Phase for Different Depth Sources



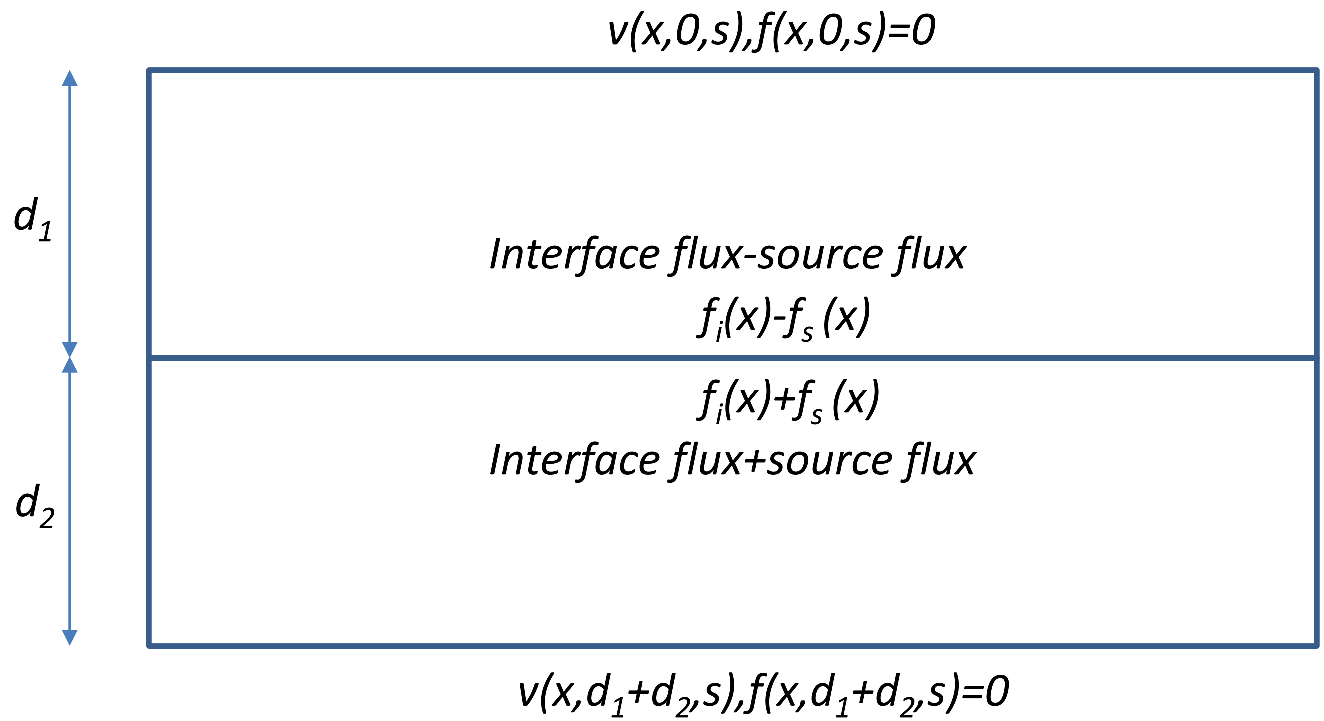
Source p |cos(ω t)| at different depths in 0.32 cm thick block, Diffusivity=0.0045 cm^2/sec

Phase is approximately linearly dependent on source depth

Estimate of depth of harmonic source based on phase – 0.084 ±0.003 cm

Delamination depth based on UT measurement – 0.06 cm

Two-Dimensional Model with Subsurface Source



- $v(x,0,s)$ found for using quadrupole method (details in paper)
- Source flux ,$f_s(x)$, is spatial variation in the heat source at the interface
- Assume $f_i(x)=P|\cos(\omega\, t)|\ \delta(x-x_0)$ – Point source 2D (Line Source 3D)

Line Source Response for P |cos(ω t)| Source at Different Depths Below Surface

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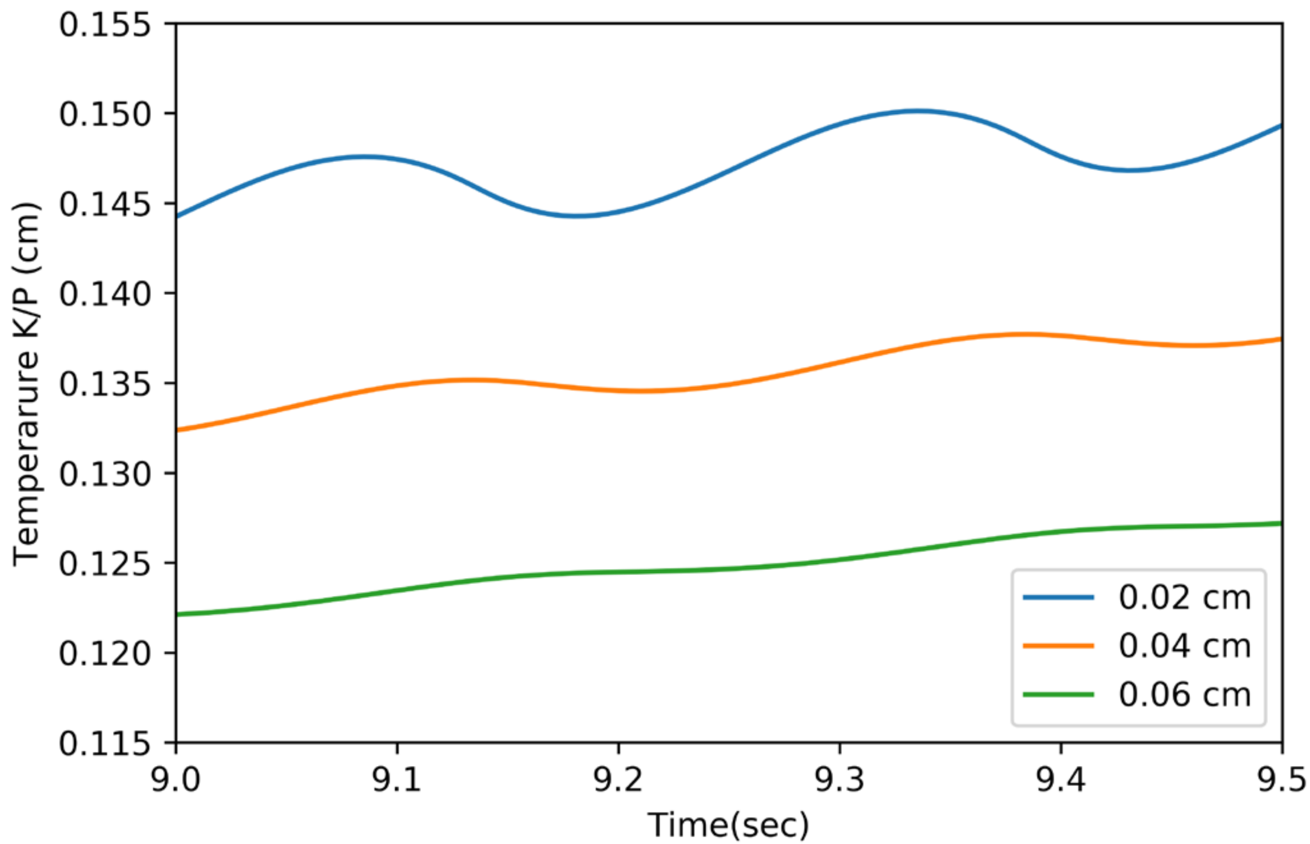

Block thickness is 0.32 cm,

Diffusivity=0.0045 cm^2/sec, Frequency=2 Hz

Amplitudes significantly less than for planar source (1D solution)

Phase is approximately the same

Comparison of Experimental and Simulation Responses

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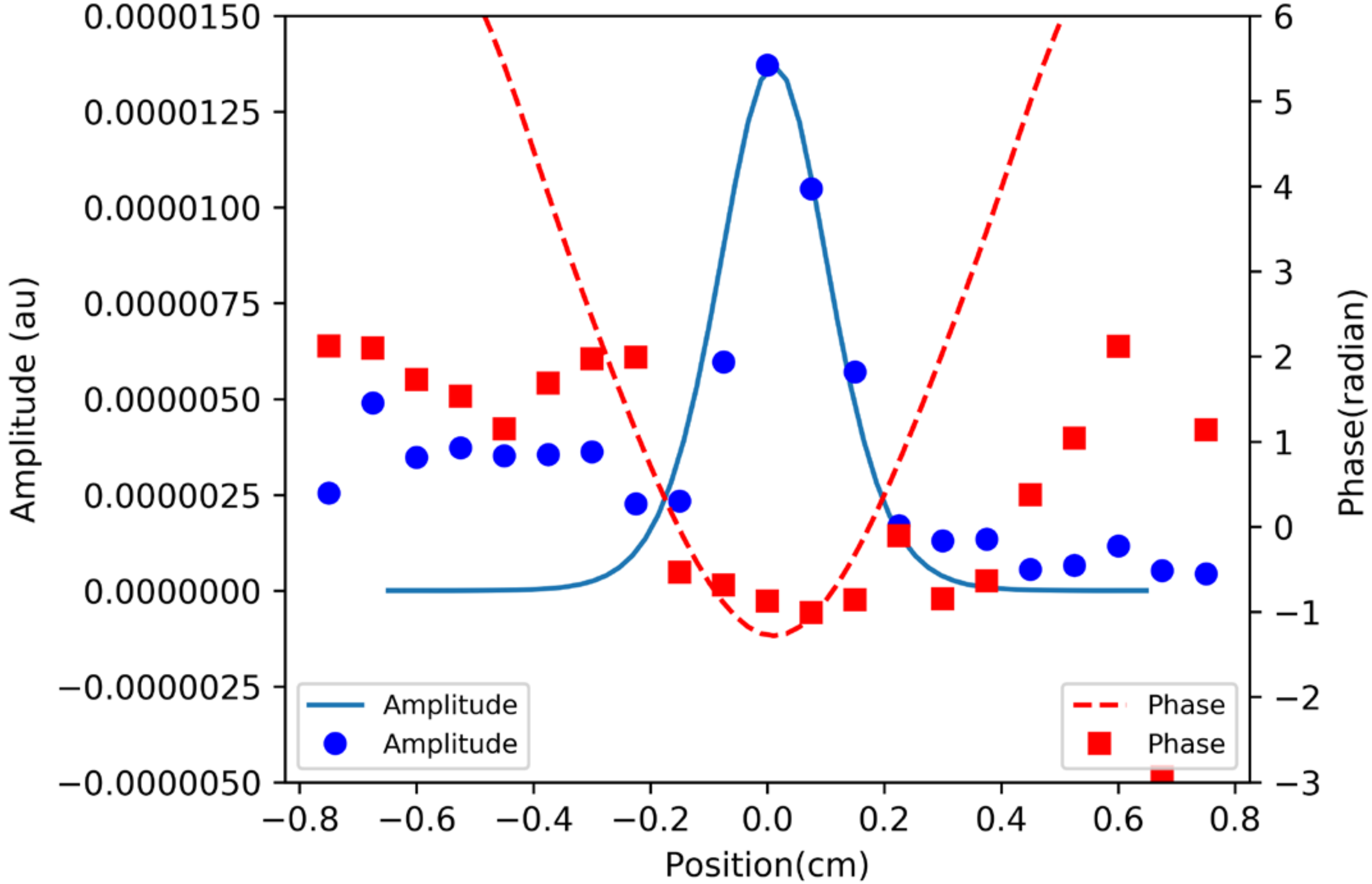

Simulation Parameters - Block thickness is 0.32 cm, Source Depth-0.085 cm
Surface Normal Diffusivity=0.0045 cm^2/sec, In-plane Diffusivity 0.025 cm^2/sec
Frequency=2 Hz

Summary

- Passive thermography has a significant harmonic at distinct locations near edges of subsurface delamination.
- Phases of all significant harmonic responses are approximately the same.
- From one-dimensional series solution assuming a simple friction source, an estimation of a source depth is 0.084 cm, which is in reasonable agreement with ultrasonic measurements (0.06 cm).
- A two-dimensional simulation is in reasonably good agreement with spatial variation of both the phase and amplitude of the measured response