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 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

I1 m M1
M2
I2

43.8 cm

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

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 – $P = F \cdot \vec{v}$ where $\nu$ is the velocity
- $\nu$ is relative movement of two surfaces of a delamination
- Assume amplitude of $F$ is constant
- Relative displacement of surfaces is proportional to $\sin(\omega t)$
- Magnitude of velocity proportional to $|\cos(\omega t)|$
- Power proportional to $|\cos(\omega t)|$
One-Dimensional Model with Subsurface Source

\[ v(0,s), f(0,s) = 0 \]

\[ v(d_1 + d_2, s), f(d_1 + d_2, s) = 0 \]

\[ f_1 + f_s \]

Interface flux - source flux

\[ f_1 + f_s \]

Interface flux + source flux

\[ v(d_1 + d_2, s), f(d_1 + d_2, s) = 0 \]

- 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 $P |\cos(\omega t)|$ Source at Different Depths Below Surface

Block thickness is 0.32 cm,
Diffusivity=0.00425 cm$^2$/sec, Frequency=2 Hz
Source $p \, |\cos(\omega t)|$ 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 – $0.084 \pm 0.003$ cm

Delamination depth based on UT measurement – 0.06 cm
Two-Dimensional Model with Subsurface Source

\[ v(x,0,s), f(x,0,s) = 0 \]

\[ v(x,d_1+d_2,s), f(x,d_1+d_2,s) = 0 \]

- \( v(x,0,s) \) 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)
Block thickness is 0.32 cm,
Diffusivity=0.0045 cm²/sec, Frequency=2 Hz
Amplitudes significantly less than for planar source (1D solution)
Phase is approximately the same
Simulation Parameters - Block thickness is 0.32 cm, Source Depth-0.085 cm
Surface Normal Diffusivity=0.0045 cm²/sec, In-plane Diffusivity 0.025 cm²/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.