Fatigue Crack Geometric Feature Extraction from AE Waveforms using Physics of Materials Based Approach

Jingjing Bao, Banibrata Poddar, Victor Giurgiutiu
Department of Mechanical Engineering, University of South Carolina, Columbia, SC 29208
baoj@cec.sc.edu, poddarb@email.sc.edu, victorg@sc.edu

ABSTRACT

Conventional acoustic emission (AE) analysis methods are predominantly based on parametric feature extraction, pattern recognition, and statistical analysis. In this study we focused on identifying geometric features of the crack from the AE signals using physics of materials based approach.

The main challenge of this approach is to develop a thorough understanding of the mechanism of generation and propagation of acoustic emissions waveforms due to the growth of a fatigue crack. As the geometry changes due to the crack growth, so does the local vibrational modes around the crack. Our aim is to understand these changing local vibrational modes and find possible relation between the AE waveforms features and the crack geometric features.

Finite element (FE) analysis was used to model AE events due to fatigue crack growth. This was done using dipole excitation at the crack tips. Harmonic analysis was also performed on these FE models to understand the local vibrational modes. Experimental study was carried out to verify these results.

Fatigue experiments were performed on several small test coupons to generate fatigue cracks. AE events were recorded during these fatigue tests. After the fatigue test, piezoelectric wafer active sensors (PWAS) were used to excite the cracked coupon, and the local vibrational patterns were captured using laser Doppler vibrometry. Preliminary results show that some of the AE waveform features can be linked to crack local vibrational modes, such as the crack fundamental vibration frequency and its higher harmonics.

Keywords: AE, acoustic Emission, fatigue crack, FEM simulation of AE, guided wave, physics of materials based approach, time-frequency analysis
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Outline

- Review AEWG-57 presentation: Acoustic Emission Events Characterization during Low Cycle Fatigue Experiments
- Work-in-progress: Fatigue Crack Geometric Feature Extraction from AE Waveforms – “Listen to the length of the crack”
- Crack local vibration mode during AE events
- Fatigue test to detect crack resonance during AE
- Excite fatigue crack rubbing with mechanical shaker
- Summary and Conclusions
- Future work
Review of 2015 AEWG-57 Presentation:

Acoustic Emission Events Characterization during Low Cycle Fatigue Experiments
Estimate AE source location

AE Channels: CH 1, CH 2, CH 3, CH 4

Clay

1mm hole

Estimated wave velocity: 5000 m/s

CH 1: +6 µs → ~29 mm

CH 2: +1 µs → ~5 mm

CH 3: +1 µs → ~6 mm

CH 4: +5.5 µs → ~27 mm

AE Source Crack

6,534.199379739

6,534.199372789

6,534.199374939

6,534.199379289
AE signal: 38 mm coupon with crack – CH3

Dominant Lamb S0 mode wavelength $\approx$ specimen width
Dominant frequency $\approx 145$ kHz

$fd \approx 73$ kHz.mm
WORK-IN-PROGRESS: FATIGUE CRACK GEOMETRIC FEATURE EXTRACTION FROM AE WAVEFORMS

“LISTEN TO THE LENGTH OF THE CRACK”
Fatigue Test: In-plane Resonance of the Crack

Crack Resonance
- 100 kHz range
- In-plane motion
- Resonance on the crack lips
- Sensor
  - High frequency
  - In-plane

Examples of some wave types

<table>
<thead>
<tr>
<th>Wave Type</th>
<th>Rayleigh</th>
<th>Lamb-S0</th>
<th>SH-wave</th>
</tr>
</thead>
<tbody>
<tr>
<td>Velocity (mm/µs)</td>
<td>2.89</td>
<td>5.4</td>
<td>3.1</td>
</tr>
<tr>
<td>Crack Length (mm)</td>
<td>20</td>
<td>20</td>
<td>20</td>
</tr>
<tr>
<td>Wave Length (mm)*</td>
<td>40</td>
<td>40</td>
<td>40</td>
</tr>
<tr>
<td>Frequency (kHz)</td>
<td>72</td>
<td>135</td>
<td>77</td>
</tr>
</tbody>
</table>

* First resonance: $\lambda/2 =$ crack length
Shaker Test: Flexural Resonance of the Crack

**Crack Resonance**
- Low kHz (below 20 kHz)
- Out-of-plane motion
- Resonance on the crack lips
- Sensor
  - Low frequency
  - Out-of-plane

**Rubbing of Faying Surfaces**
- High frequency, 100’s kHz
- Low amplitude
- Short duration
- Sensor
  - High frequency
  - High sensitivity

Cross-section showing Rubbing faying surfaces

Examples of some wave types

<table>
<thead>
<tr>
<th>Wave Type</th>
<th>Velocity (mm/µs)</th>
<th>Crack Length (mm)</th>
<th>Wave Length (mm)*</th>
<th>Frequency (kHz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lamb-S0</td>
<td>5.4</td>
<td>20</td>
<td>40</td>
<td>135</td>
</tr>
<tr>
<td>Lamb-A0</td>
<td>0.23</td>
<td>20</td>
<td>40</td>
<td>5.73</td>
</tr>
<tr>
<td>SH-wave</td>
<td>3.1</td>
<td>20</td>
<td>40</td>
<td>77</td>
</tr>
</tbody>
</table>

* First resonance: \( \lambda/2 = \text{crack length} \)
CRACK LOCAL VIBRATION MODE DURING AE EVENTS
AE Source Model

- AE source was modeled with dipoles distributed across thickness (Hamstad et al., 1999)

- The dipole strength was ramped up in time to simulate fatigue crack growth

- The ramp shape was modeled as a half-cycle cosine thus generating a smoothed-step with 1.5 μs rise time
Resonance of Hole + 5 mm Side Cracks (FEM)

Amplitude of in plane displacement at the top crack opening

Resonance at the crack

Amplitude of in plane displacement at the bottom crack opening

Resonance at the crack

FFT of AE Signal received at 5 mm from Hole (FEM)

Sensor 1

Resonance at the crack

FFT of AE Signal received at 20 mm from Hole (FEM)

Sensor 2

Resonance at the crack

Sensor 1

Sensor 2

Resonance of Hole + 5 mm Side Cracks (FEM)
Experimental Setup

- A through thickness slit was made in an aluminum plate (AL 2024 T3 1219 mm x 1219 mm x 1 mm)

- Two PWAS were bonded at a tip of the slit on both top and bottom surfaces

- Both the PWAS were excited at the same time to excite S0 mode of Lamb wave

- A laser Doppler velocimeter (LDV) was used to sense the transient wave signal
Experimental Setup

- The PWAS were excited with tone burst to simulate AE from a crack tip.
- The tone burst was designed to have a wide frequency range.
- The generated wave signal was collected at 20 mm from the crack.

![Graphs showing excitation signal in time and frequency domains.]

Excitation Signal in Time Domain

<table>
<thead>
<tr>
<th>Time (μs)</th>
<th>Relative Amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>0.5</td>
<td>0.5</td>
</tr>
<tr>
<td>1</td>
<td>1</td>
</tr>
<tr>
<td>1.5</td>
<td>1.5</td>
</tr>
<tr>
<td>2</td>
<td>1</td>
</tr>
<tr>
<td>2.5</td>
<td>0.5</td>
</tr>
<tr>
<td>3</td>
<td>0</td>
</tr>
<tr>
<td>3.5</td>
<td>-0.5</td>
</tr>
<tr>
<td>4</td>
<td>-1</td>
</tr>
</tbody>
</table>

The Excitation Signal in Frequency Domain

<table>
<thead>
<tr>
<th>Frequency (kHz)</th>
<th>Normalized Amplitude</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>0.1</td>
</tr>
<tr>
<td>100</td>
<td>0.2</td>
</tr>
<tr>
<td>200</td>
<td>0.3</td>
</tr>
<tr>
<td>300</td>
<td>0.4</td>
</tr>
<tr>
<td>400</td>
<td>0.5</td>
</tr>
<tr>
<td>500</td>
<td>0.6</td>
</tr>
<tr>
<td>600</td>
<td>0.7</td>
</tr>
<tr>
<td>700</td>
<td>0.8</td>
</tr>
<tr>
<td>800</td>
<td>0.9</td>
</tr>
<tr>
<td>900</td>
<td>1.0</td>
</tr>
</tbody>
</table>
In-plane excitation at the tip of 18-mm slit

Measured wave field using LDV shows that both the tips of the slit acts as a source even though the wave source was placed only at one tip
Signal Received at 20 mm (Experimental Result)

FFT of LDV signal

- The peaks correspond to the local resonances along the crack length
Fatigue test to detect crack resonance during AE
100-mm Coupon Fatigue Test

- 100-mm coupons tested

- **Coupon design:**
  - 1.04 mm (0.004 inch) thick, 2024-T3 aluminum plate
  - 100 mm wide, 300 mm long
  - 1 mm diameter hole at the center

- **Fatigue loading program**
  - 2.3 kN $\rightarrow$ 23 kN sine wave
  - Max. stress 223 MPa (32 ksi)
  - 65% of yield stress (345 MPa)
  - Load cycling rate: 4 Hz

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100-mm fatigue test coupons during fatigue experiments.

1. Coupon 1 is used to calibrate the fatigue loading program
2. Coupon 2 is used to capture AE during fatigue loading program
Experimental Step 1: Initiate Fatigue Crack

- Same specimen (100 mm wide, 1 mm thick Al2024 plate, 1 mm diameter through thickness hole at the center)
- No sensors were used at this stage
- The specimen was loaded axially under 23 – 240 MPa cyclic loading at a frequency of 10 Hz to initiate a crack from the 1 mm hole
- Two cracks initiated at the hole after about 28000 loading cycles
- After another 4000-5000 loading cycles, the crack grows to about 20mm total length (tip to tip) – see picture below
- The experiment was repeated for four specimens
Experimental Step 2: Grow Crack and Capture AE

- Sensors were bonded on the specimens at this stage
- A PWAS was bonded next to the crack
- An AE sensor (WSA) was bonded 50 mm away from the crack
- Clay boundary was applied to specimens
- Cyclic Loading of 60-240 MPa was used
- Loading frequency of 0.25 Hz applied
- It took about 600 cycles to grow crack to about 36 mm
Signals from PWAS

TYPE 1

Normalized Amplitude

Frequency, kHz

Time, μs

Amplitude

TYPE 2

Normalized Amplitude

Frequency, kHz

Time, μs

Amplitude

NOISE

Normalized Amplitude

Frequency, kHz

Amplitude

Time, μs
Type 1 Signals from PWAS

- Type 1 signals show non dispersive S0 mode type behavior
- The frequency band for these types of signals also PWAS tuning curve for S0 modes
Type 2 Signals from PWAS

- Type 2 signals show dispersive A0 mode type behavior
- The frequency band for these types of signals also PWAS tuning curve for A0 modes
Hypothesis based on PWAS Signals

- During the crack growth energy is released from the crack tip in the form of S0 mode as the specimen is under uniaxial tension.
- This happens when the stress cycle is at its peak.
- When the stress cycle is decreasing, the inclined crack surfaces rub against each other near the crack tip and emits acoustic emission in form of A0 mode.
- Apart from Type 1 and Type 2, there are signals received which look like having both S0 and A0 modes.
PWAS Signal Type 1

- Beginning of the crack growth from 20 mm
- At intermediate crack length 1
- At intermediate crack length 2
- Before sample failed at crack length \( \approx 36 \) mm
PWAS Signal Type 2

Beginning of the crack growth from 20 mm

At intermediate crack length 1

At intermediate crack length 2

Before sample failed at crack length ≈ 36 mm
EXCITE FATIGUE CRACK RUBBING WITH MECHANICAL SHAKER
MIL-STD-810G, Method 514.6 Annex C, pp. 514.6C-17

- Identify in-flight frequency range that may excite the crack to produce AE signals through rubbing or clapping.

15 mm crack in a 75 x 75 mm² plate might give some rubbing and clapping signals at ~ 1 kHz (FEM simulation).

Figure 514.6C-6. Category 7 - Jet aircraft vibration exposure.
FEM Prediction of Crack Rubbing and Clapping Motions

FEM Modal Analysis

Resonant Modes with Crack Rubbing Motion

- Mode 12: 2.747 kHz
- Mode 17: 4.640 kHz
- Mode 21: 5.853 kHz
- Mode 26: 8.729 kHz

Resonant Modes with Crack Clapping Motion

- Mode 9: 1.077 kHz
- Mode 14: 2.770 kHz
- Mode 19: 5.192 kHz
- Mode 20: 5.399 kHz
- Mode 24: 7.082 kHz

15 mm crack in a 75 mm x 75 mm plate
Crack opens at 1 kHz on 100-mm Coupon

First Bending Mode

\[
\begin{align*}
\text{Mode: 7 of 300} \\
\text{Frequency: 88.175 cycles/s} \\
\text{Maximum Value: 138.191 mm} \\
\text{Minimum Value: -233.62 mm}
\end{align*}
\]

~1 kHz Vibration Mode

\[
\begin{align*}
\text{Mode: 18 of 300} \\
\text{Frequency: 936.929 cycles/s} \\
\text{Maximum Value: 243.291 mm} \\
\text{Minimum Value: -357.266 mm}
\end{align*}
\]

Detail view shows crack opening at ~1 kHz mode
Crack Resonance Measurement Test Setup

Excitation:
1. Function generator: Tektronix AFG3052C
2. Power amplifier: NF HSA4014
3. Mechanical Shaker: Brüel & Kjær 4809

Data acquisition:
4. Polytec OFV 5000 vibrometer controller
5. Polytec OFV-505 sensor head
6. Tektronix TDS5034B oscilloscope

Test parameters
• Chirp excitation: 1 Hz – 5 kHz, 100 ms duration, 2 Vpp, ~1A rms
• LDV (measures velocity): 100 mm/s/V, 100 Hz HPF, 1.5 MHz LPF
Fatigue Crack Resonance @2.86 kHz: SLDV vs. FEM

Experimental

SLDV

Simulation

FEM
Fatigue Crack Resonance: SLDV vs. FEM

Experimental

SLDV @ 2.5 kHz

Simulation

FEM@ 2.8 kHz
Crack Relative Velocity at Resonance Frequencies

Vibration Amplitude: Large
Relative Amplitude: Large

Vibration Amplitude: small
Relative Amplitude: small

Vibration Amplitude: small
Relative Amplitude: Large

LDV laser beam
mounting hole for attaching to shaker

~20 mm long fatigue crack

Point A
Point B

Crack resonance?

Coupon resonance?

Vibration Amplitude: Large
Relative Amplitude: small
Comparison: FEM simulation and LDV Measurement

- FEM simulation and LDV Measurement of crack vibration velocity
  - Similar frequency contents
  - Resonance mode amplitudes are not comparable
  - Possible to improve the simulation results with real experimental data
Crack AE Wave Detection: Sensors & Frequency Range

- MIL-STD-810 Method 514.6
- Frequency Range
- Shaker Test Generated Signal Frequency Range
- Rubbing of faying surfaces
- AE Sensor
- LDV
- Ring Sensor
- Fatigue Test Generated Signal Frequency Range
- PWAS
Summary and Conclusion

- Crack generates various types of structural waves
- Crack generated waves carry geometric features of specimen and crack
- Crack generate different types of waves under different boundary conditions and loading configurations
- Appropriate sensor type and frequency range are needed to capture the crack generated waves
- “Listen to the length of the crack”
Future Work

- **AE waveform processing procedure development**
  - Build filters to identify AE waveforms come from different source types.
  - Characterize AE waveform parameters that are related to specimen geometric features.

- **Simulation technique improvement**
  - Implement the AE waveform parameters in simulation to characterize the interaction between the fatigue crack and different types of waves.

- **Experimental study**
  - Fatigue crack AE under different loading conditions – crack open and close, vibration energy level, etc.
Literature Review


Questions and comments

We need your feedback and suggestions