Can One Hear the Length of a Crack?

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Abstract

Structural health monitoring (SHM) and nondestructive evaluation (NDE) methods rely on the interpretation of ultrasonic signals. These ultrasonic signals may result from the passive capture of the acoustic emission (AE) waves emitted by a crack or from the waves scattered by the crack during an active interrogation of the structure. Current AE signal interpretation methods can identify AE events, count their rate of appearance, and even locate their location using multiple sensors and a triangulation method. To evaluate the crack size, an active SHM method is employed to relate the scatter signals with the crack size. No method to extract the crack size from the AE signals collected during passive SHM exists at the moment.

In this paper, we suggest a novel approach aimed at connecting the crack length to certain signature features that may be identified in the AE signal. One of the main challenges of this approach is to develop a physics of materials based understanding of the generation and propagation of acoustic emissions during the growth of a fatigue crack. As the geometry changes due to the crack growth, so does the local vibration modes around the crack. Our aim is to understand these changing local vibration modes and find possible relation between the AE signal features and the geometric features of the crack. 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 vibration modes. Experimental studies were performed on a specimen with a slit excited by a piezoelectric wafer active sensor (PWAS) and measured with a scanning Doppler laser vibrometry. Preliminary results show that the AE signals may carry the information related to the crack size and even geometry.

Keywords: AE, Acoustic Emission, Fatigue Crack, FEM simulation of AE, Guided Wave, Time of Flight, Physics of Materials Modeling

1. Introduction

Acoustic emission (AE) is well established as a nondestructive evaluation for monitoring the structural health by listening to the “pops” generated by the energy released during incremental crack growth [1] [2]. Passive detection of fatigue crack by AE sensing has attracted attention of many researchers for decades.

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Figure 1: Two major phenomena that generate crack-related AE signals: (a) AE generation at the crack tip as the crack advanced during cyclic fatigue or extreme-load events; and (b) AE generation by micro-fractures during the rubbing, clacking, clapping of the crack faying surfaces due to operational cyclic loading and vibration.

Existing AE equipment records these pops as so-called “hits” identified in the AE signal every time the recorded structural wave signals exceed a predefined threshold. Experimental evidence accumulated over several decades of AE practice indicates that the generation of hits accelerates as the crack enters its terminal stage close to ultimate failure. Thus an increased hit rate could be interpreted as “proximity of failure” and would require immediate action. However, the detection of hits is strongly influenced by how the threshold level is set: (i) if the threshold is too low, then “environmental noise” may trigger a large number of false hits and generate a large Type I error which annoys the crew with too many false positives; whereas (ii) if the threshold is set too high to prevent noise triggering, then the result would be a large Type II error, i.e., failure to detect an actual dangerous crack growth with the accompanying potentially catastrophic consequences. Thus setting the “correct” AE threshold remains an “art form” dependent of the subjective interpretation of experienced AE technicians. By depending on hit rates, the current AE practice does not possess an early warning capability. Such early warning capability would greatly assist the effective management of structural fatigue in coordination with allocation of mission profiles and maintenance schedules.
To impart an early warning capability to the AE process, several investigators have posit that the AE signals captured during the AE monitoring contain a wealth of information that is not properly exploited by the current AE practice which is solely based on recording “hits”. To extract more information from the AE signals, some authors have adopted a **data-driven approach** and tried to apply existing statistical signal processing methods that would extract standardized signal features such as amplitude, rise time, duration, MARSE (measured area of the rectified signal envelop), counts, moments, kurtosis, etc. [3] [4] [5]. Such AE analysis methods are based on parametric feature extraction, pattern recognition, and statistical analysis, and other data-driven methods [5] [6].

1.1. This Paper

A number of authors, including the current ones, are considering a **physics-based approach** in which the attention is directed towards understanding the origin and causation of the wave signals recorded by the AE sensors and developing the computational models to assist this process. In this paper we present our AE work with the focus on the estimation of crack length based on physics of materials and wave propagation in thin-wall structures.

![Flow chart diagram for detection of fatigue crack length from acoustic emission](image)

The objective of our study is to develop the science and understanding of how crack-generated AE wave signals can be extracted from non-crack wave signals during AE monitoring under actual operational conditions. In this paper, we summarize recent work performed in the Laboratory for Active Materials and Smart Structures, University of South Carolina, which has been focused on identifying geometric features of the crack from the AE signals using physics of materials based approach [7][8][9][10][11]. The aim of this research is to develop a method to predict crack lengths from acoustic emissions (AE) due to crack growth in plate structures. Therefore, to understand generation of plate guided waves due to crack growth and their interaction with cracks, we performed FE analysis along with experimental studies. First we introduce the experimental procedure and simplified FE modeling assumptions based on the experiment. Then we present detailed 3D FE models to elaborate our method of estimating crack length from recorded AE signal. Subsequently, we present experimental validation of our method. Finally we present our attempt to apply this method to detect fatigue crack length during fatigue test followed by conclusion.
2. The Problem and the Challenge

2.1. The Problem

The AE events are caused by various sources. Several studies have been aimed at understanding the AE generation of guided waves such as, Lamb waves, due to crack growth. Analytical models have been developed to simulate the generation of AE excitation at the crack tip and the resulting AE elastic waves traveling through the medium [13] [14] [15] [16] [17] [18]. Besides the fatigue crack, other sources such as noise, vibration, rubbing, and clacking may cause AE events that can be captured by the AE instrumentation. Two major phenomena that generate crack-related AE signals can be distinguished (Figure 1): (a) AE generation at the crack tip as the crack advanced during cyclic fatigue or extreme-load events [1]; and (b) AE generation by micro-fractures during the rubbing, clacking, clapping of the crack faying surfaces due to operational cyclic loading and vibration [12]. The AE signals of Type (a) make the object of conventional hit-based AE practice, whereas the AE signals of Type (b) are less studied because they are of much lower amplitude and are usually discarded as “noise” by the conventional AE equipment. A flowchart for the detection of crack length from these two main mechanisms of AE generation from a fatigue crack is shown in Figure 2. As shown on the left branch of Figure 2, one mechanism to be considered is that of crack growth accompanied by energy being released at the crack tip as AE waves. The other mechanism is depicted on the right branch of Figure 2: when the crack resonated due to ambient vibration, the rubbing of the crack surfaces create acoustic emissions [12].

2.2. The Challenge

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. Our main challenge is to identify crack resonances in the collected AE signals.

3. Fatigue Crack Length Detection from Crack Growth AE Signals

We follow the left branch of Figure 2 and investigate AE signals due to fatigue crack growth. Because AE is wideband excitation generally at the crack tip, our aim is to use this phenomenon to detect fatigue crack length from recorded acoustic emission signal.

3.1. FEM Simulation of Acoustic Emissions in a Plate from Fatigue Experiment

Our initial aim was to simulate AE signals recorded during uniaxial tensile fatigue test in a thin-sheet specimen representative for aerospace applications. We assume that the specimen is under pure tension and the crack is fully penetrated through the specimen thickness. Therefore, we also assume symmetric emission of acoustic energy across the plate thickness. These conditions are similar to those encountered during our experimental AE work [7]. The specimen is made of 1-mm thick 2024-T4 aluminum alloy plate. A 1-mm hole is machined in the center of the
specimen to create stress concentration for crack initiation. 3D FEM modeling was performed with the ANSYS commercial code using brick elements SOLID45. Both harmonic analysis and wave propagation analysis were performed. For wave propagation analysis, we used dipole AE sources placed on the crack tip following previous work by Hamstad and Prosser [19] [20]. The generated AE signal was captured with a sensor placed at various locations away from the AE source. To identify features of a crack from AE signals, it is important to minimize the effects of the boundary reflections. We used nonreflective boundaries [21] to prevent Lamb wave reflections from the specimen edges. The element size was chosen 0.25 mm. The time-domain profile of the dipole sources was a half-cycle cosine with a rise time $\tau = 1.5 \, \mu s$. FEM modeling of elastic wave propagation requires that the element size and the time step satisfy the Courant-Friedrichs-Lewy (CFL) condition. For material 2024-T4 with bulk longitudinal wave speed of 6.2 mm/$\mu$s, we need a time step of 40 ns or less to satisfy the CFL condition. The source rise time $\tau = 1.5 \, \mu s$ corresponds to CFL = 3. Following ref. [20], the minimum wavelength is $\lambda_m = 4.71$ mm. We use $\lambda/s = 9.4$, $\lambda/cs = 18.8$, $D/s = 40$, where, $s$, $cs$, and $D$ are element size, dipole size, and maximum distance between the source and sensor, respectively.

Figure 4: Effect of crack presence on the simulated AE signal spectrum: (a) resonances noticed in the harmonic FEM analysis of specimen with hole plus side half cracks of 5 mm each (11 mm total crack length) – no such resonances were observed when only the hole was present; (b) the spectrum of the signal received from FEM AE simulation at the sensor shows similar resonances when the 5-mm side cracks are present, but not when only the hole is present.
A schematic of the FEM model is given in Figure 3. Note that Figure 3a shows a specimen with a crack growing laterally from the hole, whereas Figure 3b shows the same specimen with only the hole. In both cases, AE dipole sources were placed in the same locations corresponding to the crack tips. The purpose of performing AE with and without the crack being present was to investigate if the presence of the crack has an effect on the AE wave signals captured by the sensor.

3.2. Crack Presence Effect on Harmonic Response

To investigate the effect of crack presence on the harmonic response of the crack, we performed harmonic FEM analysis on the specimen shown in Figure 3a. Unit harmonic excitation was applied at the dipoles and the in-plane \( u_x \) response was measured near the crack center. The excitation frequency was swept up to 2000 kHz. The size of the side cracks was 5 mm each resulting in an 11-mm total crack length. The resulting spectrum is shown in Figure 4a. It is apparent that distinct resonance peaks can be observed at a number of frequencies. When the same analysis was performed on the specimen shown in Figure 3b, no such peaks could be observed in the investigated frequency band of up to 2000 kHz. In addition, when a smaller crack (2 mm each side, 5 mm total) was modeled, the corresponding spectrum showed fewer resonance peaks which were wider spread apart. These studies seemed to indicate a clear relationship between the presence and number of resonance peaks and the length of the crack.

We believe that the observed peaks are due to local resonances of the crack due to standing waves pinned between the crack tips. Such waves could be of different types: they could be Rayleigh surface waves traveling on the faying surfaces of the crack. They could be S0 Lamb waves traveling back and forth between the crack tips. Or they could be SH0 waves. A combination of these waves happening simultaneously is also possible.

3.3. Crack Presence Effect on AE Signals

To investigate the effect of crack presence on the AE signals, we performed wave propagation analysis using the AE dipole excitation at the crack tips as shown in Figure 3a. We also performed wave propagation analysis of the specimen without crack but only with the 1-mm hole as shown in Figure 3b; in this case, the AE dipole excitation was placed on the uncracked specimen in the exact locations where the crack tips would have been if the specimen was cracked as in Figure 3a. In both cases, the AE waves were captured by the piezo wafer sensor placed at 20 mm from the center of the crack.

The results of this investigation are shown Figure 4b which presents, superposed, the Fourier transform of the AE signal for the specimen with hole + 5-mm side cracks (11 mm total crack length) and for the specimen with only the hole. It is apparent that the signal from the cracked specimen displays a number of peaks. Careful examination of these peaks reveals that their frequencies correspond almost exactly to the frequencies of the resonance peaks observed in the harmonic analysis (Figure 4a).

Another feature observed in Figure 4b is that the spectrum of the signal from the specimen without crack and only with hole displays maxima around ~450 and ~1300 kHz as well as minima at ~1000 and ~1660 kHz. Some of these maxima and minima can be also observed in the spectrum of the signal of the specimen with crack. We attribute these maxima and minima to some sort of resonance that involves the 1-mm hole.

These numerical investigations have revealed that the AE wave signal measured at a distance from the crack may carry information about the crack length. The fact that such phenomenon has not been reported yet may be due to the limitations of current AE sensors. Based on our numerical investigation, we raise the hypotheses that (i) a crack exhibits specific resonances related to its length; and (b) the AE signal generated by the energy discharged at the crack tip during crack growth may contain traces of these resonances that, upon signal processing, may reveal information about the crack length. This means that the crack length information is embedded in the AE signal and that, with appropriate skills, “one can hear the length of the crack”.

4. Experimental Investigations

In order to test our hypothesis, we cut a thin ~17-mm slit in a relatively large plate such as the boundary reflections would not interfere with the AE signal. Then, we designed an experimental setup to excite the slit and measure its response. As excitation, we used two piezo wafer active sensor (PWAS) bonded top/bottom at one of the slit tips. For measuring, we used a laser Doppler velocimeter (LDV) at ~20 mm away from the center of the slit. The PWAS transducers were excited in phase with a wideband pulse repeated in synch with LDV measurements. In this way,
we reproduced to large extend the conditions of the FEM simulation reported in the previous section. The frequency spectrum of the signal measured at 20 mm from the slit is shown in Figure 5a. It is apparent that this spectrum contains multiple peaks similar to the resonance peaks predicted by the numerical FEM simulation shown in Figure 4. To verify that these peaks are indeed resonances, we performed LDV scanning of the area around the slit. In this case, we used chirp excitation synchronized with LDV measurement at each of the scanning points around the slit. Thus, we were able to visualize the wave field around the slit at various frequencies. Some of these visualization results are presented in Figure 5b,c,d,e. Upon comparison with the frequency spectrum of Figure 5a, we were able to identify the resonance modes corresponding to some of the peaks identified in the frequency spectrum of Figure 5a. This experiment validates our FEM analysis and seem to confirm our hypothesis that crack resonance may appear due to AE excitation at the crack tip.

![Figure 5](image.png)

**Figure 5:** Resonance of the slit at multiple frequencies due to acoustic emission from PWAS (a) measured at 20 mm from the slit (b)-(e) area scan results showing standing wave field around the slit

**5. Discussion**

The results presented so far seem to indicate that the AE signals recorded during crack advance may contain embedded information about the length of the crack. This embedded information is generated by the fact that the AE energy discarded at the crack tip during crack growth may generated standing waves that would engage the crack into local resonances. These resonances are of high frequency, typically hundreds of kHz and low MHz. We hypothesize that these local vibration resonances would modulate the AE wave signal that travels away from the crack thus embedding crack-size information in the AE wave signal. We also hypothesize that these AE wave signals would travel at a distance from the crack and could be capture with appropriate AE transducers that sufficiently sensitive for this task. These AE wave signals, could be processed and decoded such as to reveal the embedded crack-size information.

Our laboratory experiments on a slit cut into a large plate have confirmed the FEM simulation results. However, this experiment is rather facile, because it ensured stress-free non-contacting faying surfaces that may not always be the case in actual operational AE work because fatigue crack may open only temporarily during the fatigue cycle. Nonetheless, our FEM modeling confirmed by laboratory experiments indicate that crack length information is may exist encoded into the AE wave signal. It is our task to continue the experimental efforts and physics-based modeling to achieve further understanding of this phenomenon and chart ways of using it in practical AE work.
6. Summary, Conclusion, and Suggestions for Further Work

Summary: Fatigue crack generated AE waves were studied with analytical simulation, numerical simulation, and experiments. Finite element method (FEM) 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.

Conclusion: The acoustic emission signals received from a growing crack may be processed to yield information about the crack length and other geometric properties. A library of features of the AE waveforms can be used to identify fatigue crack geometric features. Thus, we may be able to identify the geometric features of a fatigue crack such as crack length, and crack tip locations by "listening" to the crack-generated AE waves. The amplitude and frequency contents of the secondary wave emitting from fatigue crack resonances may be used to determine their geometric properties.

Suggestions for further work: The initial work reported in this paper should be continued with experiments performed on actual fatigue specimens. Low cycle fatigue cracks may require tensioning in order to be opened, but high-cycle fatigue cracks, which undergo much lower plastic flow during testing, may be sufficiently opened to allow crack resonances. Scanning Doppler laser vibrometer (SDLV) experiments with PWAS excitation should be followed by actual in-situ capturing of AE signals.

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References