Acoustic emission sensor effect and waveform evolution during fatigue crack growth in thin metallic plate

Md Yeasin Bhuiyan, Bin Lin and Victor Giurgiutiu

Abstract
In this article, the effect of the acoustic emission sensor on the acoustic emission waveforms from fatigue crack growth in a thin aerospace specimen is presented. In situ acoustic emission fatigue experiments were performed on the test coupons made of aircraft grade aluminum plate. Commercial Mistras S9225 acoustic emission sensor and piezoelectric wafer active sensor were used to capture the acoustic emission waveforms from the fatigue crack. It has been shown that the piezoelectric wafer active sensor transducer successfully captured the fatigue crack–related acoustic emission waveforms in the thin plate. The piezoelectric wafer active sensor transducer seems to capture more frequency information of the acoustic emission waveform than the conventional acoustic emission sensor in this particular application. We have also shown the evolution of the acoustic emission waveforms as the fatigue crack grows. The signatures of the fatigue crack growth were captured by the evolution of the acoustic emission waveforms. This waveform evolution is highly related to the physical boundary conditions of the cracks as well as the fatigue crack growth mechanism. The fatigue loading and acoustic emission measurement were synchronized using the same acoustic emission instrumentation. This synchronization provided the exact load level when the acoustic emission signals had occurred during the fatigue crack growth.

Keywords
structural health monitoring, wave propagation, fatigue crack, acoustic emission sensor, smart structures, aerospace specimen

Introduction
State of the art
Researchers of intelligent material systems and structures always strive for developing a better and reliable method for fatigue crack detection (Abraham et al., 2012; Biemans et al., 2001; Zhou and Zhang, 2014). The acoustic emission (AE) technique had been used for a long time in application to the structural health monitoring (SHM) and nondestructive evaluation (NDE) of structures (Abouhussien and Hassan, 2016; Gorman and Prosser, 1996; Morton et al., 1973; Pollock, 1989; Prosser, 1996). The AE signals from the fatigue crack had always been an interesting topic for the researchers (Bassim, 1992; Bhuiyan et al., 2017a; Hamel et al., 1981; Lindley et al., 1978; Scruby et al., 1985). However, most of the works focused on setting up the background of this technique and performed AE hit–based analyses. To use AE as an online monitoring system for the modern structures, a deeper waveform–based analysis is the demand for next generation.

AE monitoring of a wind turbine blade due to stepwise static loading was considered (Han et al., 2014). Monolithic piezoceramic patches were used to measure the acoustic waves on panel structures (Sundaresan et al., 2001). However, the simulated AEs were considered, and they were much simpler than the actual fatigue crack–related AEs. The AE waveforms can be detected using commercial piezoelectric transducers and fiber brag grating sensor mounted on the surface (Perez et al., 2001). The performances of piezoelectric wafer active sensor (PWAS) transducers were well characterized for detecting the guided ultrasonic waves in the aerospace structures (Bhuiyan, 2016; Bhuiyan et al., 2016; Giurgiutiu, 2005). However, the applicability of PWAS transducer to capture the fatigue crack–related AE signals in thin-walled aerospace structures is yet to be done.

Department of Mechanical Engineering, University of South Carolina, Columbia, SC, USA

Corresponding author:
Md Yeasin Bhuiyan, Department of Mechanical Engineering, University of South Carolina, 300 Main Street, Columbia, SC 29208, USA.
Email: yeasin85@gmail.com
The AE methods were also used for safety monitoring of the civil structures and thermal fracture of the glass materials (Kim and Sache, 1986; Li et al., 2015; Sagar and Prasad, 2012). One of the major challenges of the fatigue crack–related AE signals is that a simple fatigue experiment could generate a huge amount of AE data which could make it difficult to analyze the individual AE waveform. A Bayesian approach to analyze the huge amount of AE data was developed (Agletdinov et al., 2016). The acoustic wave energy–based method was used to characterize the different stages of fatigue damage in a round steel specimen (Ould Amer et al., 2013). They showed three clusters of waveforms, one of which had very low energy content as compared to the other two. Both analytical and finite element method (FEM) simulation suggested that the formation of a crack in the aluminum alloys emits acoustic waves (Andreykiv et al., 2010; Guo et al., 1998; Prosser et al., 1999; Sause and Richler, 2015). Many researchers attempted to use the AE monitoring for thin structural components of aircraft (Chang et al., 2009; Ernst et al., 2016; Lee et al., 2006; Lucas, 2010). Three types of elastic waves were identified during a fatigue experiment on aluminum alloy specimen (Nam and Mal, 2001). However, none of them showed exactly at what load level the AE signals had occurred from the fatigue crack.

AE signals contain a wealth of information regarding the online damage occurrence in the structures. By analyzing the AE signals, it was also possible to extract the fatigue crack length information as shown in our recently published article (Bhuiyan et al., 2017b). The acoustic waves emanating from the fatigue crack propagate as guided waves in the thin plate (Bhuiyan et al., 2017b; Jingpin et al., 2008; Maji et al., 1997). A nonlinear relation between the AE count rate and the fatigue crack growth rate was shown based on AE hit analysis (Berkovits and Fang, 1995), and the fatigue crack propagation in welded joint was also considered (Roberts and Talebzadeh, 2003). Thus, AE waveform–based analysis together with the applied load synchronization is necessary for a comprehensive understanding of acoustic waves.

**Scope of this article**

The novelty of this article is to study the applicability of PWAS transducer to capture the AE signals from the complex fatigue crack. PWAS transducers and commercial Mistras S9225 AE sensors were used simultaneously to capture the AE waveforms from the same AE events generated during cyclic fatigue testing. It was found that the PWAS transducers can successfully capture the AE signals. In addition, the PWAS captured a richer frequency content than the commercial S9225 AE sensors. Another significant aspect of this article is the study of the AE signals in synchronization with the applied cyclic fatigue load which revealed the evolution of the AE waveforms during fatigue crack growth. In situ AE fatigue experiments were performed, and the AE signals were analyzed from the point of view of both hit level and waveform level. The crack growth was optically measured from the high-resolution video recording during the AE fatigue experiment. The relation of the AE waveform evolution with the fatigue crack growth was explained.

**In situ AE fatigue experimental setup**

In situ AE fatigue experiment was designed to measure the AE signals from the fatigue crack growth under application of axial cyclic fatigue loading. A commonly used material for fatigue-prone components of the aircraft, aluminum Al-2024 T3, was used to make the test coupons. A thin plate-like specimen was manufactured. The dimension of each coupon was 305 mm in length, 100 mm in width, and 1 mm in thickness. This was a relatively longer and wider coupon than the typical dog bone–shaped smaller specimens that were tested initially. The main purpose of the bigger plate specimen was to grow longer fatigue crack before fracture and better resemblance of the actual aerospace structures. The longer fatigue crack growth would generate more acoustic waves. Furthermore, the bigger specimen would allow using wave-absorbing clay boundary around the area of interest to reduce the reflection from the plate edges. Practically, it would represent a bigger structure where edge boundary–reflected waves diminish before they reach to the sensor. The repeatability of the experimental results was confirmed by testing three identical specimens under the same loading condition.

The schematic diagram of the experimental setup is shown in Figure 1. Initially, a small 1-mm-diameter hole was drilled at the center of the test coupon. The fatigue crack was initiated from the hole after 33,000 fatigue cycles. A hydraulic MTS machine was used to apply the fatigue loading to the test coupon. A specimen mounted on the MTS grip is shown in Figure 2(a). An axial tensile cyclic fatigue loading was sinusoidally varied between a maximum and minimum load level maintaining an R-ratio ($\sigma_{\text{min}}/\sigma_{\text{max}}$) of 0.1. The maximum and minimum load levels were calculated based on the stress level of 65% and 6.5% of the yield strength of the material (345 MPa), respectively. These load levels were selected since they are commonly used load level in practical aircraft testing (Grover, 1966; John and Seneviratne, 2011).

We conducted the experiment in two stages. In the first stage, higher cyclic loading rate (4 Hz) was used to initiate and grow the crack up to 20 mm. Then, the second stage of AE fatigue experiment was conducted. The specimen was equipped with AE sensors and the wave-absorbing clay boundary.
Two sensors—(a) PWAS transducer and (b) S9225 AE sensor—were bonded symmetrically with the initial crack. PWAS transducers are commonly used for detecting the ultrasonic guided waves for SHM and NDE. S9225 AE sensors are commercially available from the Mistras-Physical Acoustics Company and are used as a wideband AE signal monitoring applications. The centers of the sensors were at 5 mm from the crack. Such proximity of two sensors allowed picking up low amplitude AE signals which would otherwise diminish due to geometric spreading and any material damping as they travel away from the crack. Furthermore, it would capture waveforms from any local interaction of the AE signals and the crack. The diameter of the PWAS transducer was 7 mm and the diameter of the S9225 sensor was 3.5 mm. The close-up views of the two sensors are shown in Figure 2(b) and (c).

To extract the far-field loading information directly from the specimen, a strain gauge was bonded at 40 mm from the crack. The instrumented specimen was then subjected to the fatigue loading. The load level was reduced to 60% of the previous load level by considering the initial crack length, and the loading was applied at a slower rate (0.05 Hz). These settings allowed fatigue crack growth in a controlled manner.

Three parallel systems were used simultaneously during the AE fatigue experiment: (a) fatigue loading by the MTS machine, (b) AE and load measurement by the Mistras AE system, and (c) fatigue crack growth measurement by a high-resolution video recorder. Since the AE recording and the load recording was performed in the same Mistras AE system, it allowed better synchronization between the load and AE measurement. The schematic diagram of the instrumented specimen with Mistras AE system is shown in Figure 1.

In the second stage, the fatigue crack grew from 20 to 30 mm as measured optically from the video recording. The numerous AE hits were captured by both sensors. Each AE hit corresponds to an AE waveform. Two identical preamplifiers with a built-in band-pass filter (30–700 kHz) were used for the two sensors. A 40-dB gain was selected for both preamplifiers. Thresholds of the two sensors were selected just above the environmental noise level. Higher sampling rate (10 MHz) was chosen to capture any high-frequency AE signals.

**Effect of the sensors on the AE waveforms**

**AE hit–based analysis: similarity between PWAS and S9225 AE hits**

The AE signals from the fatigue crack growth were captured by the PWAS and S9225 AE sensors. The AE hit plots show the similar pattern for both PWAS and S9225 as illustrated in Figure 3. Note that the AE hit amplitude corresponds to the maximum amplitude of an AE waveform converted into a decibel (dB) scale.

It can be observed from the PWAS AE hit plot that there is a baseline of AE hits at almost constant 70-dB amplitude level. Similarly, a baseline of AE hits can be observed in the S9225 AE hit plot at about 45-dB amplitude level. These baseline AE hits were named as “group A.” The inception of new AE hits occurred after 550 s, and it was observed from both the plots. The incipient AE hits were gaining the amplitudes in the “transition” period, and they became almost constant.
after 600 s. The new AE hits with highest amplitude after the transition were named as “group B.”

Although the patterns of the two AE hit plots are similar as shown in Figure 3, the AE hit amplitudes were different. The PWAS-captured group B AE hits have about 96 dB hit amplitudes and the S9225-captured group B AE hits have about 68 dB hit amplitudes. Similar AE hit amplitude difference can be observed for group A as well. This may be because the size of the PWAS transducer (7 mm diameter) is larger than the size (3.5 mm diameter) of the S9225 AE sensor. Also, they have different piezoelectric transduction factors and mechanisms of sensing.

It was observed that in PWAS capture, all the waveforms in a particular group (A or B) had almost the same time-domain signal and frequency spectrum. Similarly, in S9225 capture, all the waveforms in a particular group (A or B) had almost the same time-domain signal and frequency spectrum. However, we observed some differences between PWAS and S9225 AE waveforms as detailed in the following.

**AE waveform–based analysis: differences between PWAS and S9225 AE waveforms**

We studied the effect of the AE sensors on the captured AE waveforms. Based on the AE hit analyses as discussed in section “AE hit–based analysis: similarity between PWAS and S9225 AE hits,” we have seen that both AE sensors are in sync in capturing the AE hits. No apparent difference was observed between the two sensors from the AE hit–based analyses. We further performed a deeper level analysis, that is, AE waveform analysis.

A typical time-domain waveform and the frequency spectrum of group A AE signals captured by PWAS and S9225 at the same time are shown in Figure 4. The frequency spectra showed that the low-frequency peaks at 40 and 100 kHz are successfully captured by both PWAS and S9225 AE sensors. However, PWAS transducer captured additional 370-kHz frequency peak that was somehow missing in the frequency spectrum of S9225.

The time-domain waveform and the frequency spectrum of the AE signal during the “transition” period captured by PWAS and S9225 at the same time are shown in Figure 5. The amplitude of this particular transition AE signal was about five times higher than that of group A waveform. There was also a difference in the frequency spectrum of group A, and transition AE waveforms such as 220- and 450-kHz frequency peaks of the transition waveform were not observed in group A. The low-frequency peaks until 100 kHz were captured by both PWAS and S9225. However, PWAS transducer captured 220- and 450-kHz frequency peaks that were missing in the frequency spectrum of S9225.

Figure 6 shows the time-domain and frequency spectra of group B AE waveforms captured by PWAS and S9225 at the same time. Note that after the transition period (Figure 3), there are group A and group B AE hits. The hit amplitudes of group B AE waveforms were appeared to be constant at a higher level. The frequency spectrum of group B is similar to the transition waveform but different from group A waveforms. Figure 6 shows that the low-frequency peaks until 100 kHz were successfully captured by both PWAS and S9225. However, PWAS transducer captured 220- and 450-kHz frequency peaks that were missing in the
frequency spectrum of S9225 as marked by the dotted ellipses.

**Explanation of why S9225 was missing some high-frequency peaks**

To find the reason that the S9225 AE sensor missed the two frequency peaks in the frequency spectrum, we collected the frequency response curve of S9225 from the manufacturer (Figure 7(b)). It shows the frequency response of the sensors for a wide range of frequencies. It can be observed from Figure 7(b) that there is a weak response in the frequency range of 170–300 kHz. S9225 also showed a weak response in that frequency range as shown in Figure 7(a). This explains why S9225 was missing 220-kHz frequency peak.

S9225 was also missing 370- and 450-kHz frequency peaks as compared to the PWAS transducer. This may indicate that the high-frequency AE signals from the fatigue crack are related to the in-plane wave motion. Since PWAS transducer measures in-plane and out-of-plane motion through the in-plane strain sensing, it captured the high-frequency in-plane wave motion.

**Evolution of AE hits from the fatigue crack**

The AE signals from the fatigue crack growth were captured by both PWAS and S9225 at the same time. The

![Figure 4](image-url) "Group A” AE waveform and its frequency spectrum captured by (a) PWAS transducer and (b) S9225 AE sensor at the same time. Both of them captured low-frequency peaks until 100 kHz. PWAS captured low-frequency contents plus 370 kHz frequency.

![Figure 5](image-url) "Transition” AE waveform and its frequency spectrum captured by (a) PWAS transducer and (b) S9225 AE sensor at the same time. Both of them captured low-frequency peaks until 100 kHz. PWAS captured low-frequency contents plus 220 and 450 kHz frequencies.
load information was captured directly from the specimen by the bonded strain gauge. Since the AE measurement and the load recording were performed using the same AE machine, the timing of the load was synchronized with the timing of the AE signals. The AE hit recording for 60 fatigue cycles is shown in Figure 8. This section of the recording is chosen to be shown here because it contains a transition of AE hits. In this particular 60 fatigue cycles, the crack growth was optically measured as 300 μm. Then, the average crack growth can be calculated as 5 μm/cycle.

The two AE hit recordings by PWAS and S9225 are overlapped over each other together with the cyclic loading. The overall view of the overlapped plot is shown in Figure 8. The AE hit amplitudes are scaled in such a way that the AE hits of PWAS and S9225 can show the one-to-one correspondence, together with the cyclic loading variation. The maximum PWAS AE hit amplitude is scaled to unity, and all the other PWAS AE hits are divided by that maximum value. Similarly, the maximum S9225 AE hit amplitude is scaled to unity, and all the other S9225 AE hits are divided by that maximum value. Using this kind of scaling, we are able to merge two plots of Figure 3 into a single plot in Figure 8 without any alteration. Of course, the reader could find the actual hit amplitude in decibel scale from Figure 6.

The two AE hit plots of Figure 8 share the same scaled AE hit amplitude indicated by the left bar, and of course, the actual values can be obtained using...
Figure 3. The cyclic loadings are normalized by the maximum load level and overlapped with the AE hit plots that have already been merged. The right bar indicates the normalized load information. We would be able to show all the three plots together in a single Figure 8 using the combination of the scaling and normalizing process mentioned above.

AE hits occurred at every cycle as shown in Figure 8. PWAS and S9225 AE hits seemed to be in sync. From the overall view, the two groups of AE hits can be identified: “group A” and “group B.” There is also a transition AE hits as shown by a dotted rectangle. Before the transition zone, there are only “group A” AE hits. After the transition, there are “group A” AE hits as well as “group B” AE hits.

Figure 9 shows the zoomed in area of the dotted rectangular portion marked on Figure 8. It clearly shows the synchronization of the AE hits of PWAS and S9225 with the cyclic loading. The AE hits occurred during the cyclic loading period (from minimum load to maximum load) only. In the unloading period (from maximum load to minimum load), no AE hits were observed.

It is clear from Figure 9 that PWAS and S9225 captured the AE hits almost at the same time. It indicated that the two sensors captured the same AE event at the same time. This is true for all groups A and B and transition AE hits. New AE hits occurred through the transition and gaining amplitudes until they became group B. We observed that group B AE hits had a different waveform as compared to group A as detailed in section “Evolution of AE waveforms from the fatigue crack.”

The load levels of groups A and B and transition AE hits

In order to explain the physical relation to the fatigue crack, we wanted to learn about the exact loading level for which these AE hits occurred. The load–hit synchronization plot as shown in Figure 10 illustrates the load level of “group A” AE hits before the transition. To find the load level, a vertical line can be drawn from the AE hit to the loading cycle curve. From the intersection point, a horizontal line can be drawn to the normalized load scale on the right that gives the exact load level of that AE hit. These AE hits occurred when the load level was 85% of the maximum load. The results of the three consecutive cycles are shown in Figure 10, and all of them show the same load level of 85% F_max.

Interestingly, almost same load level was observed for all “group A” AE hits before the transition (not shown here). Since these AE hits occurred near the maximum load, they may be related to the crack growth. The fatigue crack was growing at a constant rate releasing the AE hits at a constant amplitude. The crack growth may occur at a single stage before the transition period.

The load levels of the transition AE hits are shown in Figure 11. Two pairs of AE hits can be observed in the transition period. The first pair was gaining amplitude and exceeds the second pair at some points. Figure 11
shows that the first pair of AE hits occurred at 82% of maximum loading ($F_{\text{max}}$) during cycle 1 and at 81% $F_{\text{max}}$ during cycles 2 and 3. The second pair was similar to “group A” AE hits that occurred at 85% $F_{\text{max}}$. The amplitudes of the new AE hits were increasing gradually through the transition period. In cycle 3 of Figure 11, the amplitude of the new AE hit is sufficiently larger than “group A” AE hit, and the load level of “group A” drops to 84% from 85%. The fatigue crack growth phenomenon may change during the transition period. The new AE hits may capture the change in the fatigue crack growth. A complex physical change may occur near the crack tip that could result in an unsteady crack growth during the transition period.

After the transition period, the amplitude of the new AE hits, that is, “group B,” became almost constant (Figure 12). They occurred at almost 81% of the maximum load. “Group A” AE hits occurred at almost 84% of the maximum load and had slightly variable amplitudes. Two pairs of “group A” AE hits were also observed in some cycles, for example, cycles 1, 3, and 4 in Figure 12. The same phenomena of the AE events were successfully captured by both PWAS and S9225 sensors.

In every fatigue cycle, “group B” AE hit occurred earlier with a higher amplitude than “group A” with a lower amplitude. It was observed from the video recording of the crack growth that crack grew at relatively faster rate when the two groups of the AE hits occurred. The fatigue crack growth might occur in two stages at every cycle after the transition period. The first-stage crack extension could start when the cyclic load had reached at 81% $F_{\text{max}}$ releasing a higher amplitude AE hits followed by the second-stage crack extension releasing lower amplitude AE hits.

### Evolution of AE waveforms from the fatigue crack

The AE waveforms evolved as the fatigue crack grew. This evolution was observed occurring through the transition period. Before the transition period, group A waveforms were observed, and the fatigue crack grew at a slower rate, whereas after the transition, both group A and group B waveforms were observed, and the fatigue crack grew at a relatively faster rate. The comparison between group A and group B waveforms is shown in Figure 13. Both time-domain plots and the frequency spectra were illustrated in this figure.

Group A waveform had the frequency peaks of 40, 70, 100, and 370 kHz. Group B waveform had the frequency peaks of 40, 60, 100, 220, and 450 kHz. On one hand, at 370 kHz, there was a peak in group A, whereas there was a dip in group B waveform. On the other hand, at 220 and 450 kHz, there were peaks in group B, whereas there was a dip in group A at those frequencies. Hence, there were significant differences in the two waveform groups. The amplitude of group B was several orders higher than group A waveforms. The signal-to-noise ratio of group B was also higher than group A waveforms.

When the fatigue loading reached near the maximum, the micro-structural bonding near the crack tip could be broken releasing the higher amplitude AE waveforms followed by a consecutive bonding breakage with lower amplitude AE waveforms. The change of elastic energy release could be higher during the first-stage micro-structural bonding breakage than that during the consecutive second-stage bonding breakage. Since the crack grew faster when two AE waveform groups appeared, the AE waveform evolution could be an indicator for the material failure prediction. This could be a useful parameter for an SHM design based on AE waveforms.

### Conclusion

The PWAS, commonly used for SHM application, is capable of sensing the AE signals from the fatigue crack
in the thin plate. The PWAS and S9225 AE sensors captured the same AE event at the same time. It has been shown that the AE sensor type has a significant effect on the captured AE signals. Depending on the application, one sensor could give more information than the other sensor. As an example, for this particular application, PWAS captured more information of the AE waveforms than the commercial S9225 AE sensor. The fatigue crack growth signatures can be interpreted from the evolution of AE waveforms. The experimental results have shown that the fatigue crack growth in a thin aerospace plate releases different groups of AE waveforms. The evolution of AE waveform could be an indicator for the material failure prediction. The load–AE hit synchronization performed in this study can give the exact load level for which the acoustic waves are released from the crack. The AE hit–based analysis may not be sufficient for understanding the fatigue crack–related AE signals. The AE waveform analyses give much more information than the AE hit–based analyses.

Future work

The low signal-to-noise ratio AE signals that occurred at relatively lower load level would be analyzed to find if there are any other groups of AE waveforms. The AE waveforms would be further analyzed to find any possible correlation with the fatigue crack length. In situ microscopic measurement of the fatigue crack length could be performed. This would help to establish a better correlation between the fatigue crack length and the AE signals. The AE system, MTS machine, and the optical measurement could be synchronized together for better understanding and interpretation of the AE signals.

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References


Bhuiyan MY (2016) Guided wave inspection of cracks in the rivet hole of an aerospace lap joint using analytical-FEM approach. Master’s Thesis, University of South Carolina, Columbia, SC. Available at: https://search.proquest.com/docview/1874575549?accountid=13965
Available at: http://www.ndt.net/article/ecndt2006/doc/Mo.2.1.5.pdf