Preliminary Development of Online Monitoring Acoustic Emission System for the Integrity of Research Reactor Components

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Abstract. Three research reactors owned by BATAN have been more than 25 years. Aging of (Structure, System and Component) SSC which is mainly related to mechanical causes become the most important issue for the sustainability and safety operation. Acoustic Emission (AE) is one of the appropriate and recommended methods by the IAEA for inspection as well as at the same time for the monitoring of mechanical SSC related. However, the advantages of AE method in detecting the acoustic emission both for the inspection and the online monitoring require a relatively complex measurement system including hardware software system for the signal detection and analysis purposes. Therefore, aim of this work was to develop an AE system based on an embedded system which capable for doing both the online monitoring and inspection of the research reactor’s integrity structure. An embedded system was selected due to the possibility to install the equipment on the field in extreme environmental condition with capability to store, analyses, and send the required information for further maintenance and operation. The research was done by designing the embedded system based on the Field Programmable Gate Array (FPGA) platform, because of their execution speed and system reconfigurable opportunities. The AE embedded system is then tested to identify the AE source location and AE characteristic under tensile material testing. The developed system successfully acquire the AE elastic waveform and determine the parameter-based analysis such as the amplitude, peak, duration, rise time, counts and the average frequency both for the source location test and the tensile test.

Keywords: Acoustic Emission, monitoring, embedded system, research reactor

1. Introduction

Three research reactors in Indonesia, owned and operated by BATAN, i.e. the Triga Reactor Bandung, Yogyakarta and Multipurpose Research Reactor Siwabessy, Serpong, has been operated for more than 25 years. The aging condition requires in service inspection as well as a continuous condition monitoring of the systems, structures and components (SSC) for ensuring the safe operation of the reactor. In addition a comprehensive analysis for the integrity, the characteristics and performance of the SSC will also be very important to determine further regulatory permission for the life extension of the research reactors.
IAEA provides some guidelines for the integrity inspection and leakage monitoring of the SSC which are important for the safety of the reactor, such as the reactor vessel, isolation valve, cooling pumps and primary cooling pipes [1-3]. Several methods can be applied for the in-service inspection applications and at the same time for the condition monitoring of nuclear reactors such as ultrasonic testing, vibration monitoring, acoustic monitoring (acoustic emission – AE monitoring), and guided ultrasonic wave [4]. In case of component and structure However, the acoustic emission monitoring is promising due to the advantages such as relatively unaffected to the background mechanical vibration noise or resonance [5], real time monitoring [4, 6], early detection capability [7], covers a larger area of monitoring using a minimum number of sensors compare with other structural integrity detection method [8]. In addition, acoustic emission monitoring can also applied for the structural integrity inspection in nuclear facilities [9], leakage monitoring [10, 11], early crack detections [12-14], material testing [15, 16], rotating machine monitoring [5, 7, 17, 18], corrosion indication monitoring [19]. The example of typical positions and applications of the AE for the integrity and leaking monitoring of reactor and pipe and pump of Westinghouse PWR is given in [20]. The example for the pressure vessel of EPR is in [21] while the application of VVER NPP Steam Generator can be seen in [22]. However, the advantages of AE method in detecting the acoustic emission require a relatively complex measurement system including hardware software system for the signal detection and analysis purposes [23]. The AE measurement system requires high sampling rate data acquisition system, minimum two or three sensors with simultaneous data acquisition capability for better accuracy of source location, enough memory and data storage for the signal processing analysis and diagnosis. These requirements are necessary considering the challenges in nuclear reactor which requires better accuracy under the steady state as well as the early detection of emergency condition. In addition, the AE system is required to meet the purposes for the online monitoring as well as the inspection applications in research reactor, such as for coolant leakage monitoring, early crack detection in the material of safety related components, rotating machine monitoring and corrosion detection.

To address this challenge, therefore, the purpose of this work was to develop an AE system based on an embedded system which capable for doing the online monitoring of the research reactor’s integrity structure. An embedded system was selected due to the possibility to install the equipment on the field in extreme environmental condition with capability to store, analyses, and send the required information for further maintenance and operation. The research was done by designing the embedded system based on the Field Programmable Field Array (FPGA), because of the execution speed and system reconfigurable opportunities. The AE embedded system was designed to accommodate parameter based approached and waveform-based approached. The AE embedded system is then tested by introducing simulated AE source events and tensile material testing.

2. Theory

Acoustic emission is produced when materials experience any deformations such as transient relaxation of stress and strain at a specific localized source in material [24]. This rapid and spontaneous phenomenon release several of energy, such as elastic, non-linear elastic, elastic-plastic, and elastic-viscoplastic. However, the elastic energy is mostly detected as the others are easily attenuated at short distance. Furthermore, among the elastic waves propagation modes, three of them are mostly used, i.e. Longitudinal (dilatational, P-) wave, Shear (or transverse, or S-) wave, and Rayleigh (or surface) wave. The P waves (the fastest wave), and S waves (slower than P waves), both represents the elastic waves in the sample material while the Rayleigh in on the surface.

This elastic wave energy, known also as AE event, are spread through the structures and eventually detected by AE sensors which are coupled with the sample material at the surface [25]. The AE transducer then identify this elastic energy as displacements which representation the nature of changes in the samples. The AE transducer produce electric signal based on the detected displacement under piezoelectric effect which are then amplified and processed into waveform signals for further
parameter analysis. It should be noted that the ideal transducer can detect any changes of displacements both horizontally and vertically.

The basic known method to analyze the elastic waves are AE parameters-based approached and waveform-based approached [26]. The parameter-based approached covers amplitude, energy, hits, duration and the counts of ringing identification [27] as shown in Figure 1. The parameter based approached is relatively simple, with small storage data and fast recording. On the other hand the, waveform-based approached need to records all the waveform while providing more detail analysis various fracture analysis in fault-plane orientation, size, energy and mode. The waveform analysis employs various frequency analysis, such as FFT, SFFT, wavelet, invers and correlation.

Figure 1. (a) The parameter based of AE [28] and (b) the waveform-based of AE using Continuous Wavelet Transform (CWT) [29]

3. Methodology

The research was done by designing the embedded system following several steps: performing conceptual design for the hardware and software of the AE, then followed by the development of the SE system based on the FPGA platform. The AE system was tested using generated acoustic events on a carbon steel plate with dimension 180 x 80 x 10 cm and with tensile testing. Some features of AE signal analysis, under time domain with parameter-based analysis, were also confirmed.

Figure 2. (a) The conceptual design, and (b) hardware implementation of AE system
Figure 3. The developed software for the parameter-based AE analysis using LabVIEW.

The conceptual design of the developed AE system is given in Figure 2 and Figure 3 showing the block diagram of the measurement chain system for the FPGA based embedded system and the developed parameter-based software detection system. Figure 2 shows that active sensors were employed in this paper, i.e. accelerometer, because of better AE wave conversion efficiency, better capacity in detecting any small displacements, and more immune from signal saturations even under high intensity source compare with other type of sensors. In this research, 4 AE sensors (AV-105 CISE) were employed. The preamplifiers (PA-01 CISE) were used to increase the output voltage of the signal, improve signal to noise ratio, and reduce the output impedance signals for long connector cables. Figure 2 also shows that analog and digital filter were applied in the simultaneous input modules and the FPGA module. A band-pass filter were developed to cut a low frequency of less than 1 KHz and high frequency for more than 300 KHz. Waveform analysis based on the basic feature extraction under time domain such as amplitude, the rise time duration, counts, RMS, energy and arrival time, were also determined. A special software for the detection of AE was made in this stage.

Following the AE system development, the final stage of this research are validation of the system by utilizing the statistical parameter-based test of simulated AE sources. Two type of experiments were done, i.e. fault location simulations and the tensile testing. The source fault locations may represent AE cracks, leaking or corrosion events. The AE sources ware created using pencil lead break method (2H, 0.5 mm)[4]. The generated AE were the then detected using 4 separated sensors as given in Figure 4. Furthermore, the tensile stress experiments was done as shown in Figure 5.
performance test of the AE system for the material testing is done at speed 200 mm/second using Aluminum-Magnesium alloys as one of the materials for the reactor tank and fuel cladding of RSG-GAS research reactor.

![Figure 4](image1.png)

**Figure 4.** Test arrangement for the pencil lead break acoustic emission test, (a) showing four sensors with the dimension of the iron-carbon plate testing (b) the actual photograph

![Figure 5](image2.png)

**Figure 5.** Test arrangement for tensile test- testing showing the (a) sample with sensor position and (b) tensile-test machine

4. Results and Discussions

The purpose of this work is to demonstrate the preliminary development of embedded AE system for the online monitoring of research reactors. The elastic wave of the simulated AE is detected by four sensors. The generated AE events was done using pencil lead break, first event is generated at around (50,50) cm. The result show 4 signal burst of the sensor given in Figure 6.
Figure 6 confirms that the typical burst of the AE during the test is similar with the results of common AE signals. The AE signals indicate several parameters as the AE requirements, such as amplitude, peak time, rise time, duration, and noise. Detail of the parameter analysis requires zooming of the signals (Figure 7) where the interest parameters can be identified more easily. The applied threshold was applied slightly above the noise floor at around 0.000187 V where the highest peak is detected less than 0.01 V.

The example of detected AE parameters for the sensor 1 are given in Table 1, cover the parameter-based, both on the signal parameter level and the shape of the waveform. The table shows that the duration amplitude of the peak 959 μvolt, rise time 996.2 ms, and the duration of signals 29.886 ms. The duration of time represents the time signals from the start of signal crossing the threshold until the end. The crossing signals at the threshold at the start point and the end point are around 755 μvolt and 215 μvolt respectively. The produced software, listed the detected peaks crossing the positive threshold and arrange them into a 2D array as given in Figure 7 (b) where the detected signals above and below the threshold were given sign 1 and 0 respectively. Based on this array analysis, the number counts above the threshold are about 26 counts, with the average frequency (number of counts divided by the duration time) for about 869.97 kHz. The burst signal also shows that the longitudinal (P-) wave, and the Shear (or transverse, or S-) wave were not detected while the Rayleigh (or surface) wave was dominant. The P- (primary) and S- (secondary) wave which usually precede the Rayleigh wave might be around the noise floor and hard to be detected clearly. These detected parameters clearly indicate that the system is capable of performing the online monitoring for the source faults location based on the AE events for the crack, leaking and the corrosion.

Table 1. The AE parameters for source location.

| No | Parameters                          | Values       |
|----|-------------------------------------|--------------|
| 1  | The time of first crossing signal   | 35.9128 ms   |
|    | The amplitude of first crossing     | 755 μVolt    |
|    | signal                              |              |
| 2  | The time of last crossing signal    | 65.8078 ms   |
|    | The amplitude of first crossing     | 215 μVolt    |
|    | signal                              |              |
| 3  | Time of the peak                    | 36.918 ms    |
|    | Amplitude of the peak               | 959 μVolt    |
| 4  | Rise Time                           | 996.2 ms     |
| 5  | Duration                            | 29.886 ms    |
| 6  | Average frequency                   | 869.97 kHz   |
Figure 7. The example of parameter analysis of a burst from sensor 1, presenting (a) detail of the signal (b) threshold, number of counts and the array of detected peaks, (c) the results of parameter analysis.

Further experiment is the tensile stress signals where the results are given in Figure 8. The detected signals in Figure 8 slightly different with the previous source fault location test. This test provides strength and characteristic information of the AlMg2 samples, as employed for the components of the RSG-GAS research reactor. The AE measurement is expected to detect the produced AE events mostly during the plastic transformation. The signal were acquired for more than 8 second to allow the material deformation and crack propagation can be identified. Figure 8 shows that the maximum burst at around 0.005 Volt is between 6 and 7 second.

The parameter-based approached analysis is given in Figure 9 demonstrating the detail analysis. Threshold was applied at around 0.5 mVolt producing 291 counts. The detail analysis shows that key parameters for the amplitude of the peak, rise time, duration, and the average of frequency are 3.22 mVolt, 28.0108 msecond, 0.100851 second, and 2885.46 kHz respectively as listed in Table 2. These recorded parameters show the Rayleigh wave during the plastic deformation before the crack occurs. Following this Rayleigh wave burst, several small burst indicate that the crack growth occur may attenuate the AE elastic wave to the sensors and it is hardly also detected by both sensors. The result shows that the AE embedded system able to meet the requirement for further tensile test experiment which also can be used to confirm any crack growth during the online monitoring of research reactor components.

Figure 8. The simulated burst of the two sensors during the tensile test analysis.
Figure 9. The parameter-based analysis of a burst from sensor 1 in tensile stress, presenting (a) detail of the signal (b) threshold, number of counts and the array of detected peaks, (c) the results

Table 2. The AE parameters for the tensile test.

| No | Parameters                        | Values       |
|----|-----------------------------------|--------------|
| 1  | The time of first crossing signal | 6.29423 second |
|    | The amplitude of first crossing signal | 1.18 mVolt  |
| 2  | The time of last crossing signal  | 6.39508 sekon |
|    | The amplitude of first crossing signal | 0.885 mVolt |
| 3  | Time of the peak                  | 6.32224 second |
|    | Amplitude of the peak             | 3.22 mVolt   |
| 4  | Rise Time                         | 28.0108 msecond |
| 5  | Duration                          | 0.100851 second |
| 6  | Average frequency                 | 2885.46 kHz  |

The source location and tensile testing results prove that AE signals are identified clearly than the signal noises. Compare with the various typical AE source such as in [28], the signals can be clearly validated containing the required AE parameters which illustrates the AE elastic Rayleigh wave. The tensile test signal parameter even though has smaller amplitude, the AE embedded system is capable of sensing as well as defining the characteristic of signals.

5. Conclusion

It can be concluded that the development of an embedded AE system based on the FPGA has successfully detected the AE events for the online monitoring of components in research reactor. The performance was demonstrated through source location and tensile testing. Both of these tests denote the capacity of crack, leaking and corrosion detection for an online monitoring system. The AE embedded system successfully provide parameter-based analysis approached such as the peak of the amplitude, rise time, duration, counts and the average of frequency. These parameter-based results also indicates that this preliminary development system can be applied further to determine the coordinate of the AE events as well as to present the characteristic material of components during the crack growth before jeopardize the safety of the research reactor in general.
6. Acknowledgement

I would like to thank to the Centre for Nuclear Reactor Technology and Safety for the support of funding through DIPA 2015 and 2016 and the NDT facilities at the BPFKR division. I would to acknowledge the support of head of the research centre, Dr. Geni Rina Sunaryo, head of BPFKR, Drs Deswandri MEng, and the head of laboratory of NDT, Alim Mardi, ST, MSc.

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