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Event Extraction of Acoustic Emission using Wavelet Packets and Correlation Analysis

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Abstract: **Acoustic emission signals are high frequency stress waves that are generated by rapid release of energy due to an initiation/growth of cracks, material dislocations etc. Sources of noise are present in applications where the AE testing environment is disturbed by mechanical vibrations and other background noise. Both AE signal and noise are high frequency signals and digital filters are not effective to extract the AE signal from the observed continuous signal. Wavelet packets can be used more efficiently to denoise the signal and retrieve the signal of any desired frequency range. From the denoised signal AE event can be extracted by envelope detection and correlation analysis. Since wavelet packets can give better time-frequency resolution than other transforms, it is more suitable for locating defects also which is a major application of AE testing.**

Index Terms: Acoustic emission, Pressure testing, Time-frequency resolution, Wavelet packets, Burst signal, Envelope detection, Correlation analysis

I. INTRODUCTION

Acoustic emission testing is a non destructive testing technique to monitor defect formation and failures in structural components such as steam pipes and pressure vessels used in industrial and space applications. The AE sensors are used to pick up the elastic stress waves from the material and convert them into an electrical signal. This electrical signal is further processed by filters, amplifiers and a signal processing unit. AE testing is a real time process mostly carried out in noisy environment. AE data normally contains a lot of high frequency noise like mechanical noise, hydraulic noise, electrical noise etc. These superimposed background noises makes it difficult to identify the original signal. Thus it is not possible to classify whether the specimen under testing as faulty or not.

Denoising of the signal obtained is necessary since the sources of noise are unavoidable practically. AE signals are high frequency signals in the range of hundreds of KHz. In addition these are very feeble signal having amplitude in the range of mV. The use of digital filters for signals at sampling rates of MHz is not efficient. Considering frequency analysis tools like Fourier transform and STFT gives no time information or fixed time resolution [1]. In case of AE testing time information is very important. In this paper we use wavelet packet to analyse the AE signal for denoising with a better time-frequency resolution. Envelope detection and correlation analysis are used further to extract the AE events embedded in denoised signal.

II AE TESTING METHODOLOGY

A. Signal Acquisition

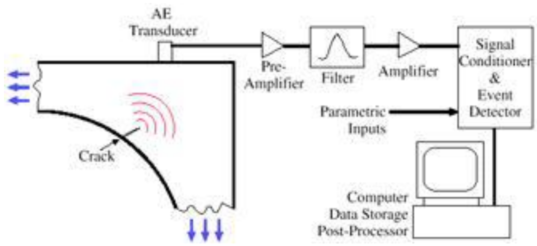


Fig. 1. AE Signal Acquisition

Typical AE test systems contain a sensor, preamplifier, filter and amplifier, along with measurement, display, and storage equipments [4].

Sensors convert the AE signal into an electrical voltage signal. The transducer element in an AE sensor is almost always a piezoelectric crystal. The output of each piezoelectric sensor is amplified through a low-noise preamplifier, filtered to any extraneous noise and further processed by suitable electronic equipment. The majority of AE equipment is responsive to movement in its typical operating frequency range of 20KHz to 1MHz. [12].

B. Signal Parameters

For analysis purposes the five most commonly used AE signal parameters of an event are amplitude, counts, duration, rise time and measured area under the rectified signal envelope(MARSE), also known as signal strength. Amplitude is the highest peak voltage reached by an AE signal waveform. Counts are the number of times an AE signal exceeds the threshold value. Rise time is the time between first threshold crossing and the peak amplitude while duration is the time between first and last threshold crossings [3].

The useful signals for AE testing of large pressure vessels are burst type signals. Continuous signals received from sensor are mostly unwanted signals [13]. It is very important to determine the characteristics of the genuine signal that lets us distinguish the wanted from unwanted bursts.

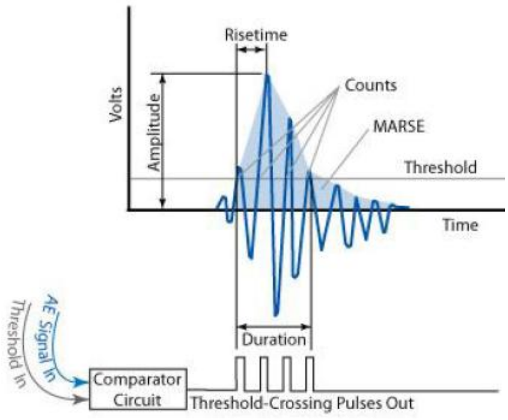


Fig. 2. AE signal parameters

C. Signal Analysis

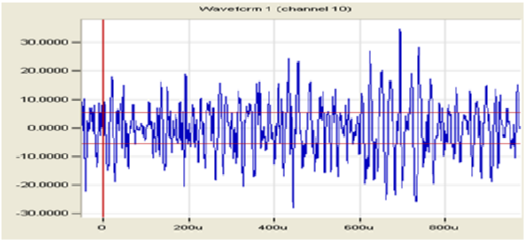
A local material change like a crack giving rise to acoustic emission is known as an event and if the AE signal captured by sensor exceeds a set threshold value it is recorded by the data acquisition system and is known as a hit. Threshold value is set in order to remove lower level noises and is often dependent upon experimental conditions. The peak amplitude is one of the most important burst features. Crack signals show medium to high amplitudes and have duration of approximately 10µs depending on the test object's properties. In most cases, bursts with less than three threshold crossings and durations less than 3µs can be regarded as unwanted signals [13].

III. PROBLEM DEFINITION AND PRELIMINARIES

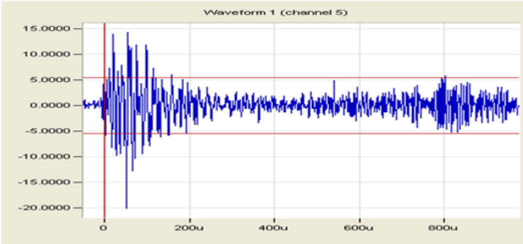
A. Proof Pressure Test

AE testing has a significant role in aerospace programmes. It is used for monitoring a wide variety of structures and components ranging from simple fluid transmission pipelines to large nuclear pressure vessels. A major problem with AE technique in the context of real-time monitoring of critical spacecraft components is that of detecting the true AE activity in the presence of various spurious AE sources such as hydraulic noise, jet engine noise, aerodynamic noise, crack face rubbing etc.

AE testing is carried out in two stages, pressurization period and holding period. During pressurization period an air jet at very high pressure is applied on the specimen for a duration of about 250s. This is carried out in a very noisy environment where the sources of noise like jet noise, vibrations etc. are unavoidable. Holding period is for a duration of next 200s during which no external pressures are applied. The test specimen is in an isolated environment. A number of sensors are fixed on the specimen for data acquisition. AE signals from any active cracks or faults are detected by the sensors and processed throughout the test. During the pressurization period all the sensors detect uncountably continuous hits. This is because the sensors detect the high frequency noise signals and these signals are interpreted as AE events and gives continuous hits. So it is not possible to detect the presence of a fault or an active crack in the specimen under pressurization. We have to analyse the noisy signal so that the AE events can be extracted from this noisy signal, if present. During the holding period a few no:of hits are recorded which are genuine AE signals. These signals are considered as reference signals in the analysis.



(a) Pressurization period



(b) Holding period

Fig. 3. Sample data

B. Traditional Methods

The simplest and most commonly used analysis procedures are estimation of cumulative counts, cumulative events, event and count rates. These kinds of analysis have often been very useful for obtaining warning of impending failures. By increasing or decreasing the threshold level some of the AE events may not be detected. Therefore in studying the behaviour of a source such as a crack in its early stages these procedures appear to be deficient [15].

The random character of AE signals gave way to use statistical methods like signal parametric plots as per event basis with respect to time or load or any other parameter of interest. This method makes use of mean signal parameter plots, distribution plots of each individual signal parameter and distribution plots with respect to time or load. The objective of this type of analysis has been to observe and quantify trends in the individual signal parameters. These are univariate analyses involving a single signal parameter individually and independently. Since AE signal is random in character, a multivariate approach is a more appropriate method for the AE analysis [15].

C. Advantages of Wavelet Analysis

AE testing has the important application of determining fault locations. In this analysis time information is an important factor that is to be considered. In fourier analysis time information is completely lost. So it is not suitable for localising faults with respect to time. STFT gives a fixed time resolution irrespective of whether the signal is high frequency or low frequency. AE signal frequency is a characteristic feature depending on the material of specimen and also on the source type. So fixed window size is not able to get the time information of all frequency components. Wavelet transform of a function is a two parameter transform representing scaling (s) and shifting (u) [17].

Wavelet transform has very flexible time-frequency resolution. As we dilate and translate the mother wavelet, we can see very low frequency components at large scale while very

$$F(s,u) = \int_{-\infty}^{+\infty} f(t)\frac{1}{\sqrt{s}}\psi^*\left(\frac{t-u}{s}\right)dt \qquad (1)$$

high frequency components can be located precisely at small scale. The signal component of a desired frequency range can be reconstructed without losing the time information [1]. In

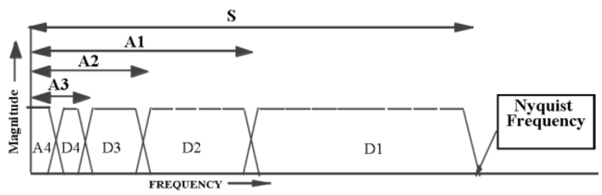


Fig. 4. Wavelet decomposition

wavelet analysis the signal is decomposed into approximation (low frequency) components and details (high frequency) components in the first level. In the following levels the approximation component alone is further split into approximation and detail. In applications like denoising and compression it is the approximation component that is considered as the useful signal. So the details components are insignificant so further analysis is not done.

In case of AE signal, the high frequency components are significant and cannot be considered noise. Since details components also contain the AE signals, further analysis of details component is needed. We use wavelet packets to analyse the noisy signal that we obtained during the real time testing.

D. Wavelet Packets

The wavelet packet method is a generalization of wavelet decomposition that offers a richer signal analysis. Wavelet packets offer a more complex and flexible analysis because in wavelet packet analysis the details as well as the approximations are split. Each detail coefficient vector is also decomposed into two parts using the same approach as in approximation vector splitting. For an n-level decomposition, there are n+1 possible ways to decompose or encode the

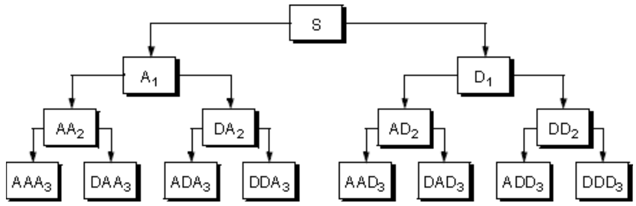


Fig. 5. Wavelet packet decomposition

signal.

The wavelet functions sequence is given by:

$$W_{2n}(x) = \sum_{k=0}^{2N-1} h(k)W_n(2x-k) \qquad (2)$$

$$W_{2n+1}(x) = \sum_{k=0}^{2N-1} g(k)W_n(2x-k) \qquad (3)$$

where $W_0(x) = \varphi(x)$ is the scaling function and $W_1(x) = \psi(x)$ is the wavelet function. It is possible to reconstruct the signal in any frequency range without losing the time information. We can locate more accurately the position of any faults. The level of decomposition is determined by analysing the frequency components present and the required frequency range. By analysing the wavelet coefficient plot for the entire decomposition , it is possible to obtain the time information and the corresponding frequency components simultaneously. This time-frequency data is used in analysis to appropriately locate the defects.

IV. PROPOSED METHOD OF ANALYSIS

In this paper we use wavelet packets to analyse the observed signal. Analysis aims at the extraction of pure AE signal from the observed noisy signal. The sampling frequency of all signals is 1MHz. Analysis of observed noisy signal is done relative to the analysis of the reference AE event. It is done in two stages, denoising and event extraction. All the analysis is done in Matlab using its Wavelet Toolbox [18].

A. Denoising

Wavelet Packet decomposition: The frequency distribution of wavelet packet decomposition is as shown in fig.6. Since the sampling frequency is 1MHz the maximum frequency content present in the signal is taken as 500KHz. The decomposition is done till level 3 which gives frequency resolution of 62KHz. It can be observed that in order to get the higher frequency components we need to decompose the details coefficients of level 2. Hence wavelet packets is the suitable transformation for the analysis [11].

Frequency Analysis of Genuine AE signals: Frequency is the main parameter that is considered in this analysis. The frequency spectrum of the reference signals is obtained as shown in fig.7. From the spectrum analysis it is observed that in the reference signals the principal component occurs around 100KHz and 150KHz. High amplitude is also seen around 290KHz and 380KHz for one of the reference signal.

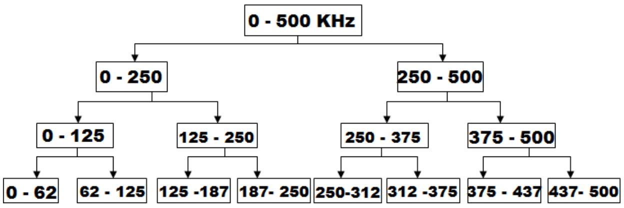
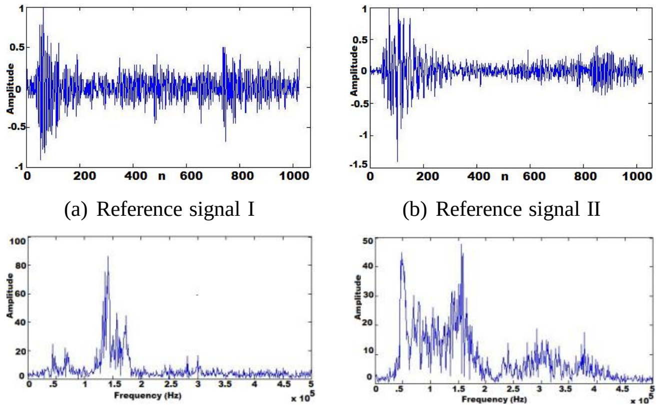


Fig. 6. Wavelet packet decomposition of reference signal

So we consider one more parameter, energy distribution of the frequency components of the genuine signals as a reference [11].

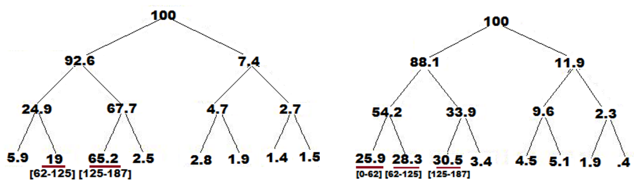


(a) Reference signal I (b) Reference signal II

(c) Frequency Spectrum of 7(a) (d) Frequency Spectrum of 7(b)

Fig. 7. Reference signals and Frequency spectrum

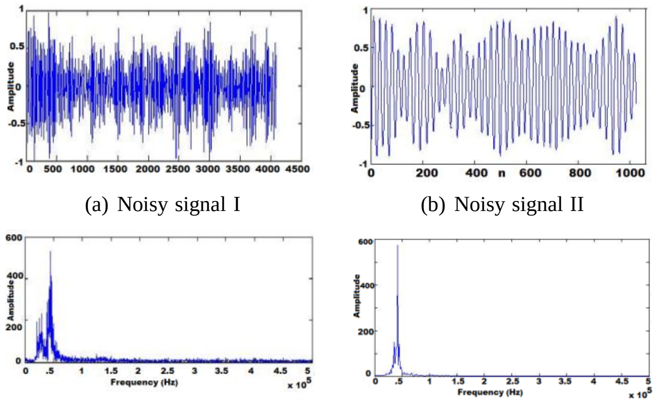
Energy Distribution of frequency components: The energy distribution on the frequency components is taken. It is obtained as shown in fig.8 From the distribution it is observed that the highlighted components constitute almost 85% of the total energy. Thus by analysing both the frequency and energy factor of the reference signals, the AE signal of the corresponding specimen lies within this frequency range. Here we use symlet8 wavelet. Since the signal is in high frequency range and to get a more precise frequency resolution we use a wavelet having higher regularity.



(a) Energy distribution of 7(a) (b) Energy distribution of 7(b)

Fig. 8. Energy distribution of reference signals in %

Frequency Analysis of noisy AE signals: Noisy signals during pressurization and the corresponding frequency spectrum are shown in fig.9. Both are signals from two different sensors. It can be seen that we cannot detect any AE event directly from the signals during pressurization.

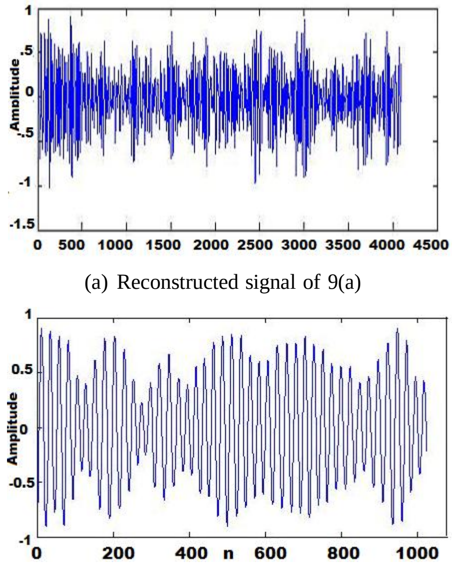


(a) Noisy signal I (b) Noisy signal II

(c) Frequency Spectrum of 9(a) (d) Frequency Spectrum of 9(b)

Fig. 9. Noisy signals and Frequency spectrum

Reconstructed signal: From the frequency spectrum and energy distribution of reference signals we have the frequency range in which genuine AE signals lie. So from the decomposed frequencies of noisy signal, we can detect those specific components which are in the frequency range of genuine AE signals. The reconstructed signal is the denoised output which is shown in fig.10. The reconstructed signal contain AE events which are embedded in noise of same frequencies. So we need to extract those events from the denoised output. For this we use the signature of a genuine AE event which has specific features.



(a) Reconstructed signal of 9(a)

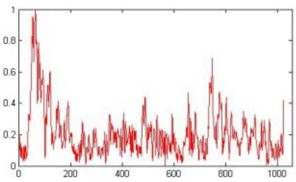
(b) Reconstructed signal of 9(b)

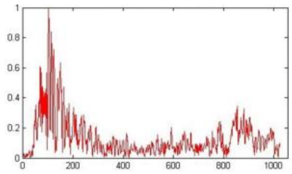
Fig. 10. Denoised output

B. AE Event Extraction

Envelope detection: AE events are burst type signal. There are certain parameters that define an AE event. To get the features we detect the envelope of genuine AE signal

[10],[12]. By considering amplitude and duration of an AE event we extract the reference envelope. We fix a threshold for amplitude and the reference envelope is considered for a duration till the signal decays below that threshold. The envelope of genuine signal and the reference envelope extracted are obtained as shown in fig.11 It can be seen that the envelope


(a) Envelope of 7(a)


(b) Envelope of 7(b)

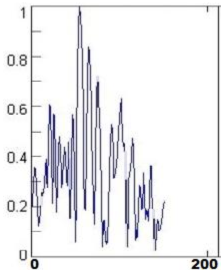
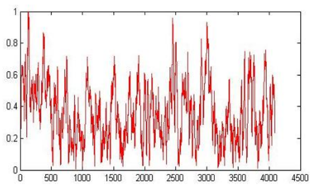

(c) Reference envelope

Fig. 11. Envelope of genuine AE signal and Reference envelope extracted

is a decaying one.

The envelope of the denoised signals are detected and are obtained as shown in fig.12. The envelope is a continuous one.


(a) Envelope of 10(a)

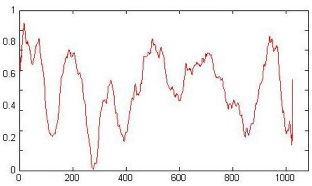
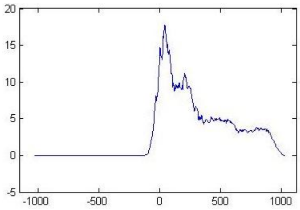

(b) Envelope of 10(b)

Fig. 12. Envelope of denoised signals

Correlation Analysis: Now we need to detect whether an event matching the genuine AE event is present in the denoised signal. The reference envelope acts as the sliding window. This window is used to find a matching pattern in the envelope of denoised signal. This is done by correlation analysis [16]. The correlation of reference envelope and genuine AE signal was computed. It is as shown in fig.13 There is a sharp peak and then the correlation decays suddenly. The peak correlation occurs only for a short duration. The correlation of reference envelope and envelope of denoised signal is computed. It is obtained as in fig.14. A sharp peak and then suddenly decaying pattern of correlation is observed in 14(a). This pattern occurs a few no:of times in this case. In fig.14(b) we see a flat correlation which is not decaying. So we can infer that there is an AE events are present in case I


(a) Correlation of 11(c) and 11(a)

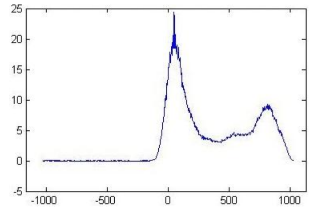
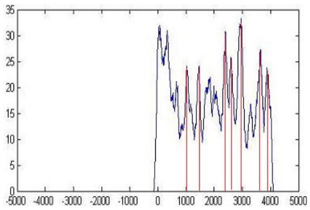

(b) Correlation of 11(c) and 11(b)

Fig. 13. Correlation of reference envelope and genuine AE envelopes


(a) Correlation of 11(c) and 12(a)

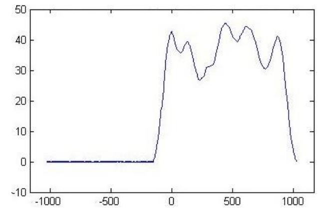

(b) Correlation of 11(c) and 12(b)

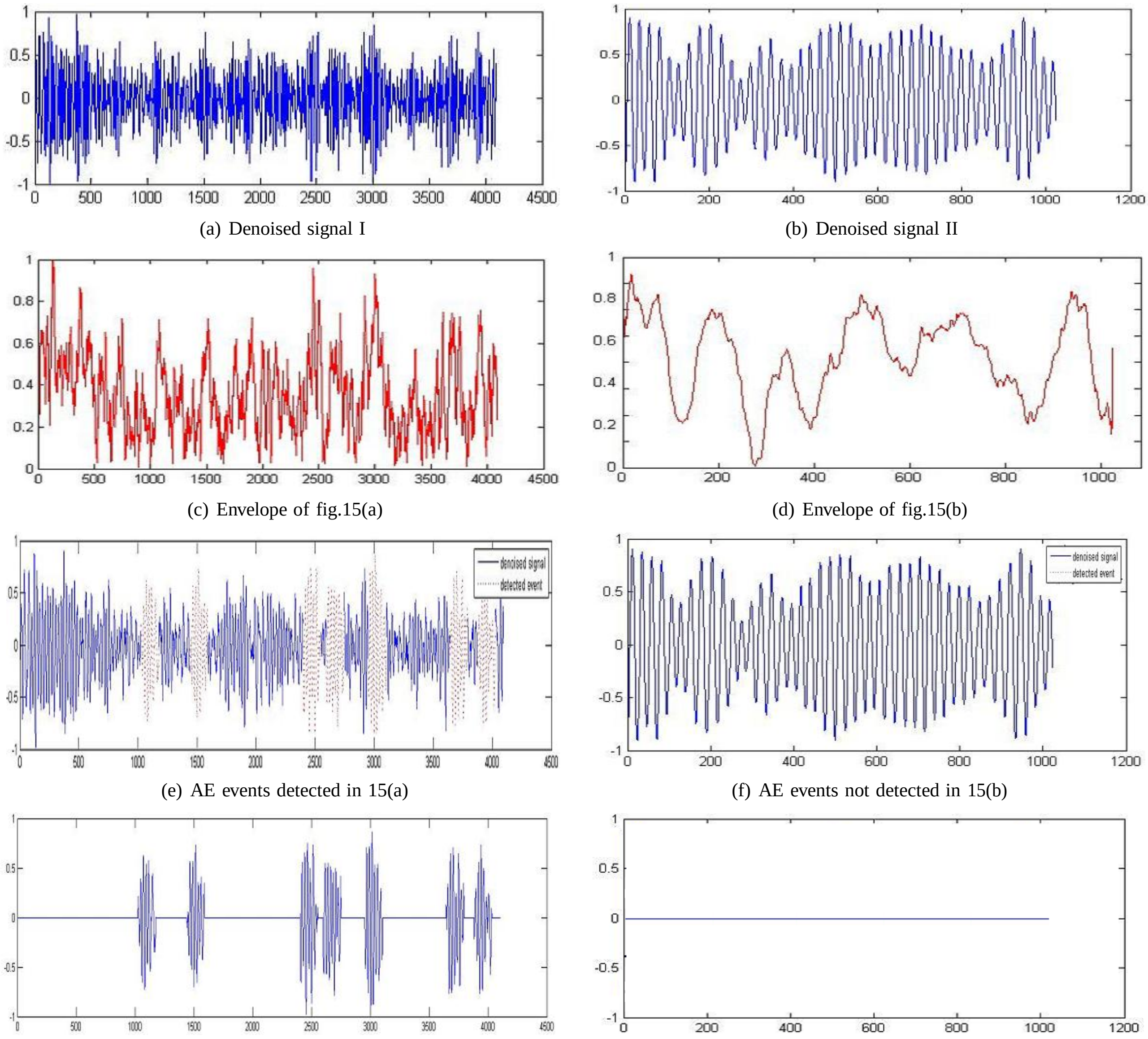
Fig. 14. Correlation of reference envelope and denoised signal envelope

at lags of peak correlation while AE event is not detected in case II. A threshold correlation is determined from the correlation of genuine AE signals. An AE event is detected only if there is a sharp rise above and a sharp fall below that threshold, which determines the burst characteristics. The peak correlation occurs at seven lags. From the denoised signal we extract the signal from that particular time to the duration of the reference envelope at all these lags. Thus it was possible to detect AE events and extract the embedded events from the signals obtained during pressurization. The result obtained is shown in fig 15.

V. CONCLUSION AND FUTURE SCOPE

The real time AE testing is always done in noisy environment. The signal observed is superimposed by noise making it impossible to detect AE events. Locating the position of defects need the time information also. By applying wavelet packet analysis we were able to get a better frequency-time resolution. The information of frequency and energy from the genuine AE signal is used to extract the frequency components of AE event that may be present in the signal occurred during pressurization. By analysing the features of an AE event we can extract the event that is embedded in the denoised signal. The analysis is done using the available sample data. This method of analysis can be used to detect and classify AE events from various types of sources, if we have a large database of different genuine AE signatures.

In this paper for the event extraction we used the threshold amplitude and time duration of an AE event as the parameters to detect the events. We can use other parameters like slope of the envelope, no:of counts, rise time etc. to extract AE events embedded. As more parameters are considered, more precise detection is possible.



(a) Denoised signal I

(b) Denoised signal II

(c) Envelope of fig.15(a)

(d) Envelope of fig.15(b)

(e) AE events detected in 15(a)

(f) AE events not detected in 15(b)

(g) AE events extracted from 15(e)

(h) No AE events in 15(f)

Fig. 15. Result obtained for two types of signals during pressurization

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