Advanced Filtering Methods Application for Sensitivity Enhancement during AE Testing of Operating Structures

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Abstract

Background/Objectives: The article considers different filtering methods for acoustic emission data. The discussion of data filtering algorithms is aimed at improving the noise immunity of the acoustic emission system. Method: Noise filtering methods (frequency filtering, time series disorder detection, etc.) are examined for AE testing. Findings: One problem of the acoustic emission testing is a great number of noises affecting the diagnosis results. Electric noises, electromagnetic interference, background acoustic noise, rubbing noises are far from the full list of noises available during measurements. At the high level of noises, the operator has to increase the recording threshold of the acoustic emission impulses through reducing the testing sensitivity at the risk of missing a dangerous defect. Lack of the data filtering can result in an incorrect localization and erroneous definition of the danger level of acoustic emission source. Different noise types have been investigated and noise classification method according to the filtering complexity has been suggested to solve effectively the problem of the acoustic emission test data filtering. Wavelet-filtering efficiency for white stochastic noise removal has been shown. Algorithm for impulse noise filtering has been described. Improvements: The offered data processing approaches allow enhancing the sensitivity of AE testing especially for the operating structures.

Keywords: Acoustic Emission (AE) of Operating Structures, Signal Processing, Time Series Analysis

1. Introduction

Acoustic Emission (AE) method has a number of advantages over other testing methods. It is a passive method based on registration of acoustic signals which arise during defect growth and plastic flow of tested object material.

AE method has high sensitivity for crack detection, does not require scanning of the tested object surface and provides remote control of the tested object sections with dimensions from several to hundreds meters. As opposed to classical testing methods (ultrasonic, magnetic, radiation methods) AE method allows ranging detected defects by their hazard rate. Hazard rate of the defect (AE source) allows estimating material deformation and destruction processes, and this estimation is the basis for defining the tested object serviceability.

Signals which are obtained during AE testing are time series of single AE impulses which are generated at random times and characterized by various AE parameters – amplitude, energy, duration, rise time. AE impulses are measured against the background of acoustic noises from the tested object and electrical noises of the AE measuring hardware.

If noise level is low, detection of defect by AE method is easy to get. Defect as AE source is revealed by AE activity and typical high amplitudes of impulses. At the same time detection of defect against high noises background is a nontrivial task connected with high variability of noise sources and specific nature of AE testing. AE activity of
defect is short time and has impulse nature as noises are continuously active, thus, the cumulative energy of AE from defect could be lower than the noise energy.

Current work considers noise filtering methods for AE testing, different noise types are investigated and different filtering methods are examined – as simple as frequency filtering for electromagnetic noise removal and as sophisticated as detection of time series disorder for AE impulses detection against impulse acoustic noise.

2. Concept Headings

2.1 AE Signals and Noises

Figure 1 shows a single AE impulse. A single impulse is an elementary item of AE signal and it contains information about a single act of destruction which is performed by AE source. AE impulse is characterized by amplitude, rise time, fall time and spectral properties.

The AE signal (Figure 2) is a set of single AE impulses which correspond to the processes of defect growth and plastic flow of the tested object. For AE signal description the following parameters are used: the number of AE impulses (counts), the number of arising impulses per unit time (activity). In addition, during AE signals analysis different parameter distributions are considered – time intervals between neighboring impulses, amplitudes and durations of single AE impulses.

The noises which are recorded during the acoustic emission testing are highly varied. They can be caused by various physical reasons, such as sensor noises, imperfection of a measuring route, and technological noises of the tested object. The noises can be essentially different in the signal waveform. They can be stochastic and determined, stationary and nonstationary, broad-band and narrow-band.

To solve effectively the problem of the acoustic emission testing data filtering a method of noise classification was suggested – according to the filtering complexity

The noises are divided into the three groups. Those types of noises which can be successfully removed by means of traditional filtering methods, such as impulse and harmonic noises, belong to the first group, as well as the low-frequency and high-frequency noises lying outside the informative range of frequencies. Such noises can be easily removed by means of the frequency or median filtering.

Signal samples corresponding to electrical and electromagnetic noises are shown in Figure 3: Figure 3a depicts electromagnetic noise caused by violation of electromagnetic compatibility, Figure 3b demonstrates pulse electrical noise, and Figure 3c illustrates quasi-harmonic electrical noise on the frequency divisible by utility frequency.
Now, only one type of noises is related to the second group – a stationary white or color noise. Such noise nature is specific for hardware noises, noises of the pumps, which performs loading of AE tested object, and noises which arise with liquid or gas flow induced by leakage of the tested object. Noise signal from gas flow is shown on Figure 4.

The filtering complexity lies in the fact that both the white noise and the impulse signal are broad-band processes, which are complicated to divide by means of the traditional frequency filtering. To detect impulses of acoustic emission against the background of the stationary white noise, the algorithm of filtering is used herein based on a discrete wavelet-transform.

The noises which are similar to the acoustic emission signals by both the shape and the spectrum are related to the third group. These are generally technological noises of the tested object, such as rubbing, vibration, various hydrodynamic noises, etc.

Such signal sample is shown on Figure 5. As the single AE impulse by its shape and spectrum is similar with the single noise impulse, during filtration the consideration is based on the processes globally, rather than on the single impulses.

Impulses induced by noise sources arise, as a rule, continuously, periodically or at random times. Process of AE impulses generation is more determined one, as it is connected with stress concentration in the material of the tested object.

3. Results and Discussion

3.1. Filtering of Noises Similar in waveform to Acoustic Emission Signals

The noises similar in waveform to acoustic emission signals are of particular complexity for filtering. These are the noises generated by various mechanical reasons – knocks, knocks of foreign objects and precipitations. The noises of this kind also occur at heating the tested object and at various hydrodynamic phenomena, for example, resulting from cavitating.

Such noises differ from acoustic emission signals neither in waveform, nor in spectrum. Thus, neither of the methods mentioned above is suitable for their filtering. The fundamental difference of the noise process and the plastic deformation process is a distinct regularity of generation of impulses characterizing one or another process. Times of impulse recording relevant to the noise action are spread quasi-uniformly (as in case of knocks or precipitations) or in accordance with the Poisson’s law (in case of cavitating or heating effect). Impulses characterizing an active source of acoustic emission (defect) follow the complicated distribution law, which parameters vary as defect develops. The defect impulses are recorded, as a rule, far rarely, and times of their recording bring a dis-harmony in the form of a certain trend to the distribution law of the background noise impulses.

Experiments with AE signals obtained in the laboratory conditions while testing the sample under low-cycle fatigue were performed to reveal the ability of AE impulses detection against impulse noise background. Noise samples were measured at plant environment by mounting AE transducer on the surface of the operating heat-exchange apparatus.
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AE signals were obtained while testing a flat sample with dimensions 220x100x2mm under low-cycle fatigue. Breakdown tests were performed using INOVA IK-6033 electric servo hydraulic unit (Figure 6).

A-Line 32D multi-channel AE system, manufactured by “INTERUNIS, Ltd”, was used to record the signals. GT-200 of “GlobalTest, LLC” sensors were used as AE transducers. PAEF-014 preamplifiers of “INTERUNIS, Ltd” had pass band of 30 – 500 kHz and 26 dB gain.

![Figure 6. Experimental assembly for samples test.](image)

Loading was performed before occurrence of the first micro-crack, which was detected by AE system, while micro-crack was occurring, burst of activity was observed – dozens of AE impulses with high amplitudes were generated. Typical AE signal that corresponds to the cracking process is shown on Figure 7a. The signal contains several hundred AE impulses that arise aperiodically – moments of the maximum defect activity are at t=0.5, 2.3, and 2.8 s. Figure 7b illustrates the plot of time intervals Δt between neighboring AE impulses. Axis of abscissa contains numbers n of AE impulses in order of their appearance and axis of ordinates contains values of Δt. The plot proves aperiodic character of AE impulses generation, impulses are generated as packages with 1-1.5 s intervals between them, mean value of time interval between neighboring impulses in package being 0.01-0.1 s.

![Figure 7. a) Fragment of AE signal corresponding to crack growth b) time series of interval Δt between neighboring impulses.](image)

Figure 7a shows noise signal. The signal was obtained by measuring enclosure wall vibration that was induced by heat-exchange apparatus operation. Noise sources here are vibration, turbulent flow of liquid and cavitating.

As Figure 8a shows, impulse components with amplitudes ranging from 2 to 8 mV prevail in the noise signal. On the basis of amplitudes and durations differences of noise impulses it could be concluded that the noise signal is a non-stationary one. However, as noise processes are conditioned by the stochastic and independent noise sources, rate of noise impulses occurrence corresponds to the Poisson distribution, which leads to regularity in distribution of time intervals Δt between the neighboring noise impulses. Figure 8b shows Δt(n) plot, where n – is a number of the interval, dependence Δt(n) has regular periodic character.

![Figure 8. a) Impulse components with amplitudes ranging from 2 to 8 mV prevail in the noise signal.](image)
Analysis of Figure 7 and Figure 8 reveals that nevertheless destruction and noise processes have similar signals in the time domain, they have big difference in $\Delta t(n)$ dependence. This difference is based on the difference in the nature of the observed processes.

With additive character of noise in mind, for further investigations AE signal and noise signal superposition was made (Figure 9a), which modeled the case of defect detection against background of acoustic noise from operating facility. As Figure 9 shows, AE impulses which correspond to defect growth are masked by acoustic noise impulses. However, on the plot of $\Delta t(n)$ dependence (Figure 9b) defect activity is manifested in disorder of regularity and stationary state of time series. While recording the signals that correspond to defect activity, the time interval values between neighboring impulses ($\Delta t$) are decreased, which leads to disorder in signal periodicity by occurrence of short time disorder. Thus, for AE impulse detection against impulse acoustic noise background, methods of time series disorders detection could be applied.

Methods of time series change point detection form the whole class of data analysis methods, which allow determining the moment of change in time series properties\cite{7}. Application of such methods to AE data flow allows detecting the defect with relatively low activity against continuously active technological noises of equipment under testing.

Complicity of detection depends on the defect development stage. The active macroscopic defect could be revealed on the basis of the $\Delta t(t)$ series if the series contains intervals with $\Delta t$ value sufficiently lower than the mean value. At the same time ‘subcritical’ crack with small size and low rate of growth could be detected against the noise background on the basis of time series analysis only with application of special mathematical methods as due to low AE rate of such a defect $\Delta t(t)$ time series properties are highly determined by the noise process.
Figures 10a and 11a show AE activity and total emission for crack at the different stages of its development. At the first stage, whereas crack size is about 0.2 mm, AE activity is not higher than 20 pulses per second and total emission of the stage during its monitoring is 725 AE impulses. At the second stage the crack size is about 2.5 mm – AE activity has increased until 30 and total emission of the stage during its monitoring is about 1,000 AE impulses.

Figures 10b and 11b show $\Delta t(t)$ and $\Delta t_i(t)$ time series corresponding to stage 1 and stage 2 of the defect growth which activity is monitored against the turbulent flow noise background.

At the first stage defect activity is manifested in the time series parameters locally (momentarily). The defect presence is expressed in local decreasing of $\Delta t(t)$ values and change of probability distribution. For the time series without defect activity (zone II), $\Delta t$ distribution has an exponential character (Figure 10c), while at the moments when AE impulses which correspond to the defect growth are recorded (zone I), $\Delta t$ distribution is improvised and differs from the exponential one (Figure 10d). For the histogram in Figure 10c at the moments corresponding to the noise process, $\Delta t$ distribution is exponential with 80% probability, and at the moments corresponding to defect activity $\Delta t$ distribution (Figure 10d) is exponential with probability lower than 4%.

For advanced stages of defect growth the detection task is solved with more certainty. $\Delta t(t)$ time series that is a superposition of noise $\Delta t$ time series and the time series corresponding to the hazardous defect with the critical activity is represented in Figure 11b. The time series in this realization has 3 distinct intervals with sharp decreasing of $\Delta t$ values, these intervals correspond to defect activity rushes shown in Figure 11a.

As $\Delta t$ values decrease is significant enough, the moving average $\Delta t$ value could be used as informative feature that characterizes defect activity. In the current case the sliding window with the size of 100 samples was used. The moments of defect activity could be found where moving average value lies under the threshold (Figure 11c – solid black line).

Function shown in Figure 11c as the solid black line is a set of strobes which are made on the basis of momentary mean values. Zero values of the function correspond to momentary mean values beneath the threshold and reveal the moments of defect activity. Non-zero values of the function reveal stationarity of the $\Delta t(t)$ series and correspond to the noise.
During AE testing of operating object it is recommended to record AE data only at the moments when strobe function has zero values which could lead to avoiding more than 90% of ‘false’ AE impulses.

The correctness of data processing results is sidewise proved by localization picture in Figure 12 where located AE sources are shown, x-axis shows distance in meters and y-axis shows the number of AE-events which take part in the location. Figure 12 shows localization for the signal from Figure 11b where AE activity of the defect is mixed with noise. The zone in the red ellipse corresponds to correct locations of the defect, other parts of diagram show false locations induced by noise. Localization in Figure12a is performed for the full realization of the signal, and localization in Figure 12b is performed for moments when strobe function has zero values. False locations shown in Figure 12b are rare and the defect is confidently extracted against the noise.

4. Conclusion

The paper considers different filtering methods for AE data. Wavelet-filtering efficiency for removal of white stochastic noise is shown. Algorithm for impulse noise filtering is described. The offered data processing approaches allow enhancing the sensitivity of AE testing, especially for the operating structures.

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6. References