A Signal Processing Method for Hits Detection and Separation in High AE Activity Systems: Application to Composite Materials under Fatigue Tests.

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A SIGNAL PROCESSING METHOD FOR HITS DETECTION AND SEPARATION IN HIGH AE ACTIVITY SYSTEMS: APPLICATION TO COMPOSITE MATERIALS UNDER FATIGUE TESTS.

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ABSTRACT

Acoustic Emission (AE) signals can be classified into three types of transients: bursts, continuous and mixed. Continuous signals consist of multiple overlapping transients emitted from different emission sources among which noise could be found. This noise might sometimes bury relevant information about the integrity of the monitored structures. The threshold-based technique, employed by most of the commercial parameter-based AE systems for hit detection, uses a defined threshold in order to detect the start and the end of the hits. When dealing with continuous emission, the threshold-based technique is not suitable as the burst never drop below the threshold. In this case, the AE system is obliged to force the end of the hit after a defined maximum duration. This issue is encountered in complex systems such as in Organic Matrix Composites (OMC) fatigue tests where a high AE activity is observed, especially when the loading frequency overpasses few hertz. In this case, continuous signals can be generated by the background noise and rubbing, as well as by both cumulated damage (friction of crack surfaces) and damage growth.

This paper deals with continuous AE signals obtained from experimental tests carried on Carbon Fiber Reinforced Plastics specimens. A numerical routine was implemented allowing the treatment of these signals. As the size of each acquisition is large due to the sampling rate (generally from 2 to 5 MS/s), the signal was divided into short segments. The Discrete Wavelet Transform (DWT) was used for signal denoising after adapting a certain number of parameters. Hit detection and determination was thereafter performed in order to localize potential hits contained in each signal segment. Conventional AE features were then calculated. By comparing the obtained results to those of conventional threshold-based techniques, we remark that the problem of erroneous hits is overcome. AE information that was hidden by the effect of the noise is now revealed allowing a further interpretation of damage mechanisms in the composite.

KEYWORDS : *Continuous AE signals, Carbon Fiber Reinforced Plastics, Fatigue tests, Wavelet denoising, Hit detection and determination.*

INTRODUCTION

Organic Matrix Composites (OMC) and especially Carbon Fiber Reinforced Plastics (CFRP) have seen an increased use in several fields such as aerospace, automotive and civil engineering, due to their high material properties. In numerous applications, metals are being replaced by CFRP composites, whose mechanical properties are increasingly improved (high strength-to-weight ratio, corrosion and heat resistance ...). Acoustic Emission (AE) technique has been widely used during these recent decades for inspection of CFRP composite structures due to its efficiency to detect and localize damages [1–3]. AE is dependent on some basic deformation and damage mechanisms. In CFRP composites, major damage mechanisms are delamination, matrix cracking, debonding, fiber cracking, and fiber pull-out [4].

Acoustic Emission signals can be classified into three types of transients: bursts, continuous and mixed [5, 6]. Bursts are generally short time-signals induced by the emergence of defects according to one or more of the damage modes. Continuous signals consist of multiple overlapping transients emitted from different emission sources among which noise could be found. Mixed transients include both bursts and continuous signals and are generated by both accrued damage (friction of crack surfaces) and damage growth and, in many cases, superimposed with ambient noise and rubbing [7]. This kind of transients is frequently encountered in CFRP composites under fatigue testing during which the specimen can be simultaneously submitted to various solicitations (tension, compression, torsion, and shear) [8]. In addition, the composite inhomogeneity resulting from the difference in material properties of the fibers and matrices will engenders an anisotropy in the velocity of the propagating waves [9].

In fatigue tests, most of the used machines (uni-axial or multi-axial loading) are working with hydraulic energy to apply desired motions. Such tests can last a long time (quasi-static loadings), which makes the hydraulic fluid hotter. In this environment, a lot of noise is often generated. In fact, uneven flow characteristics and pressure waves are created and transmitted through the fluid. This is known as *fluidborne noise* whose the pressure wave fluctuations create in turn corresponding force fluctuations. Consequently, this results in a vibration also known as *structureborne noise*, which is transmitted through the structure [10]. The AE signals received by the distributed sensors are affected by this noise. However, most of the commercial parameter-based AE systems employ the conventional technique based on both threshold and timing parameters for hit detection. A so-called 'Maximum Duration' of each detected hit is defined in the system configuration in order to stop recording of long signals. When dealing with continuous emission, the threshold is permanently exceeded, so the AE signal is recorded entirely as the burst never drop below this threshold. Thus, the conventional AE technique is not suitable, as it is, when dealing with continuous signals.

One of the powerful methods of signal denoising is Wavelet Transform (WT) [11]. Among the applications of the WT theory is the Wavelet denoise method. The WT has been used in many studies [12, 13] related to the Structural Health Monitoring field dealing with flaw-detection problems. The Wavelet denoise method has shown a good signal-to-noise ratio improvement much better than obtained through some designed filters, and an important ability in processing signals for detecting multiple fault signatures [14, 15]. Particularly, some studies have reported on the AE signal denoising based on the WT. Feng Y. *et al.* [16] have studied the denoising problem of AE signal to detect bearing defect on a rotating machine by using Discrete Wavelet Transform thresholding methods. Satour A. *et al.* [17] have developed a continuous wavelet denoising technique and applied it on AE signals obtained from cross-ply composite specimens.

This work deals with continuous acoustic emission in an in-service like environment. For that purpose, a signal processing method is developed for the purpose of conditioning continuous signals caused mainly by ambient noise encountered in fatigue test machines. The time signals are streamed during the test for each sensor. The implemented method uses the wavelet transform to denoise the affected signals after determining optimal denoising parameters that suits with our working conditions. Once the entire signal is denoised, the hit determination is carried out using the conventional threshold method. Practically, a Pencil Lead Break (PLB), as a *Hsu-Nielsen* source, is performed on the surface of the composite under low and high noise levels. Indeed, a PLB is an aid to simulate an acoustic emission event using the fracture of a brittle graphite lead. This break generates an intense acoustic signal, quite similar to a natural AE source, that the sensors detect as a strong burst [18]. The effectiveness of the implemented method is assessed thereafter by comparing some determined features to those obtained by a commercial AE system.

In this paper, the first section gives an overview of the adopted methodology and the used processing techniques. In the second section, the experimental study is addressed. It includes the manipulations performed on a composite ring using a PLB under different noise levels.

1. AE DATA PROCESSING

1.1 The signal processing method

The proposed method is schematized in Figure 1. It consists in several steps in which the continuous emission signal is post-treated after being recorded continuously with a sampling rate of 2 MS/s. Firstly, the signal is loaded. Two possible ways are considered: either the entire signal is processed one shot, or it is partitioned into equal time segments. The second way is adopted when dealing with massive data signals due to a high sampling rate and a long acquisition time. The signal is then denoised using the Wavelet Transform. Afterward, the signal or segment is swept in order to determine potential hits. Using the separated hits, AE features are thereafter computed and stored.

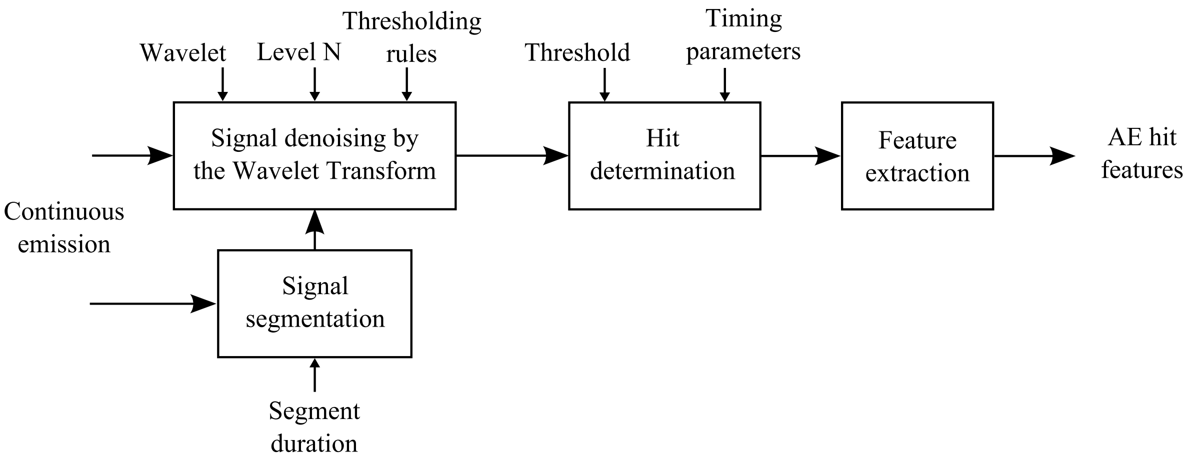

Figure 1 : Principle of the AE signal processing method.

1.2 Wavelet signal denoising

The typical procedure of signal denoising using the wavelet theory involves three steps. This procedure is used in this work and it includes:

1. Decomposition: after selecting a wavelet, the signal is decomposed by the wavelet transform at a chosen decomposition level N.
2. Thresholding: after obtaining the detail coefficients, a thresholding is applied to these signal details for each level from 1 to N. Various threshold selection rules exist (fixed form, Stein's Unbiased Risk Estimate principle...) and either a soft or hard thresholding can be applied to the signal [19, 20]. A basic model of the noise has to be taken into account for the thresholding strategy.
3. Reconstruction: computing the reconstructed signal using the original approximation coefficients of level N and the modified detail coefficients of levels from 1 to N.

1.3 Hit determination

The hits detection technique used by most of the commercial parameter-based AE systems involves comparing the signal to a defined threshold. This latter is typically set just above the noise and is maintained fixed during the test, or sometimes floating within a defined interval under conditions of high and varying background noise. If the signal surpasses the threshold, a hit is detected and this instant is retained. After detecting the hit, the timing parameters (PDT, HDT and HLT) are usually used in the conventional method in order to determine the hit, i.e. isolate and separate it from the acquired waveform. Once the hit has been determined, AE hit based features can be calculated. Conventional features include Amplitude, Duration, Energy, Counts, Counts-to-peak and Rise time [21]. Moreover, some frequency features exist such as Average Frequency, Frequency Centroid and Peak Frequency.

2. Experimental Applications

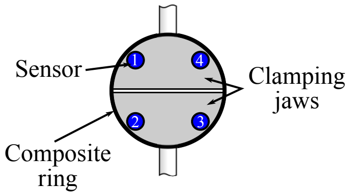

Figure 2 : Test configuration.

In this section, two test configurations are performed using simple experimental AE signals with different noise levels created by the hydraulic system of a tensile machine. This setup is designed in order to simulate an in-service like condition. In both configurations, a simple AE burst is generated using a PLB on the outward surface of an intact specimen. The first configuration is performed under a low noise level, while the second one is done under a high noise level. The test specimen is a 1.5 mm thick CFRP composite ring with an outer diameter of 124 mm and a width of about 16 mm. It is mounted on a tensile testing machine using two clamping jaws (two half-cylinders) as illustrated in Figure 2. These two jaws are not in contact, so the wave propagation is guided only by the composite ring. Four wide-band AE sensors (*'Micro80' - Mistras Group Ltd.*) with an operating frequency range of [200 – 900] kHz and a resonant frequency of 325 kHz are employed. They are equidistributed and fixed directly on the jaws in this manner: Sensors 1 and 4 are on the upper half-cylinder, whereas sensors 2 and 3 are on the lower half-cylinder. It should be mentioned that the hydraulic system is located at the bottom of the machine and is in direct contact with the lower half-cylinder. Consequently, sensors 2 and 3 are intended to be more affected by the generated noise. Table 1 regroups the major AE system settings.

Table 1 : AE system setup parameters.

Threshold	Pre-Ampli.	Analog Filter	S. Rate	PDT	HDT	HLT	Max. Dur.
40 dB	20 dB	20 kHz – 1 MHz	2 MS/s	60 μs	120 μs	300 μs	200 ms

2.1 A PLB under a low noise level

The first configuration consists in performing a PLB on the outward surface of the composite near the sensor $N^{\circ}1$. This PLB is done just after the machine is started, so that the hydraulic system is not yet producing a lot of *fluidborne noise*. This test is considered as having a low noise level. Figure 3 shows the Duration-Amplitude graphs of the hits detected by the AE system for the four channels. First of all, after a verification of the waveforms obtained from this test, it should be mentioned that the PLB hit is the point having the maximum amplitude in the graphs. In the case of channels 1 and 4, some hits other than those corresponding to the PLB are detected. However, channels 2 and 3 detect a lot of hits with relatively high durations and low amplitudes. This is due to the ambient noise that overpasses the threshold and so launches the hit detection. For the purpose of increasing the signal-to-noise ratio, the affected channels' signals can be denoised and processed by the implemented algorithm. Each channel's signal is loaded and a denoising is performed using a *Daubechies* wavelet. Consequently, the noise level is greatly reduced under the threshold and the number of the corresponding detected hits is decreased as we can see in Figure 4.

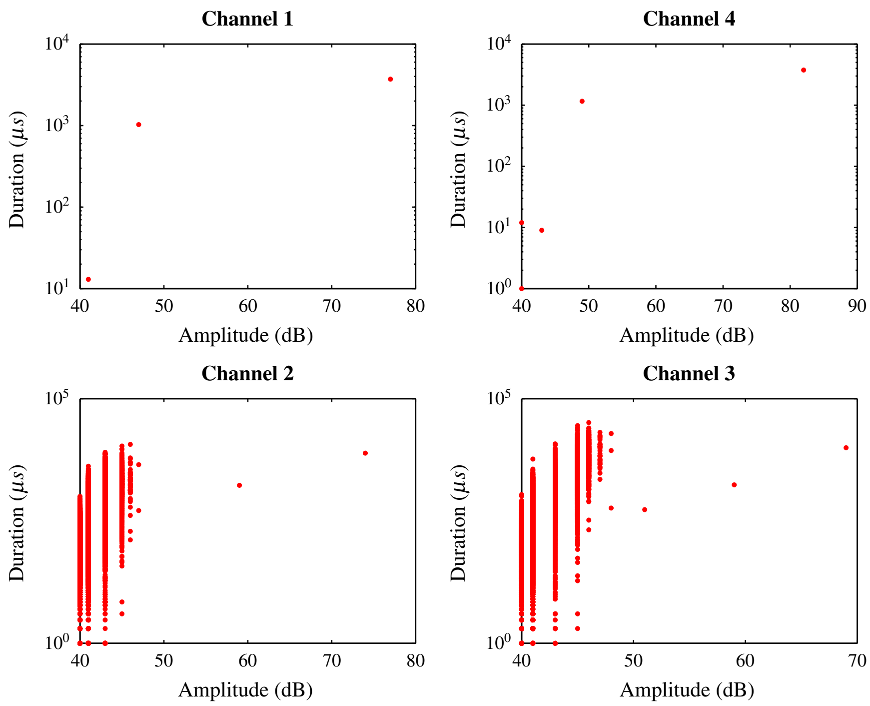

Figure 3 : Duration vs. Amplitude graphs of the detected hits by the AE system from the four channels after a PLB under a low noise level.

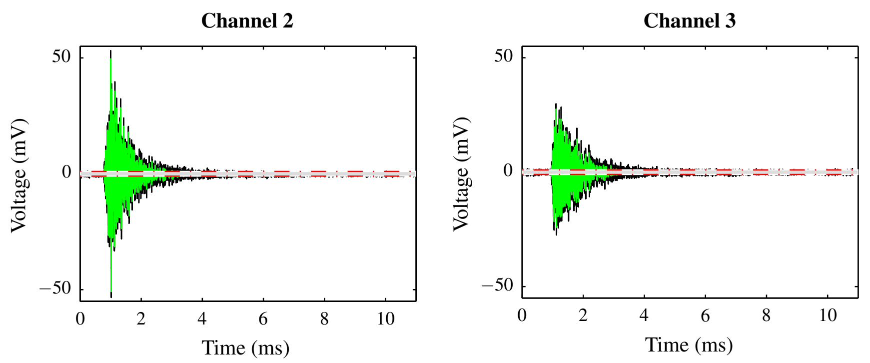

Figure 4 : Comparison of the raw and denoised signals of channels 2 and 3 after a PLB under a low noise level. (——) Raw signals; (——) denoised signals; and (−·−) threshold level.

2.2 A PLB under a high noise level

In the second configuration, another PLB is created but well after the first test in the same place as the first configuration, so that the fluid in the hydraulic system reaches a high fluctuations' activity.

A higher noise level is then generated. Figure 5 shows the Duration-Amplitude graph of the hits detected by the AE system for all channels. All the detected hits are accumulated at a duration of 200 *ms*, which corresponds to the predefined maximum duration. Indeed, as we can see in Figure 6, the recorded signals are so noisy (especially for channels 2 and 3) that the amplitude never drops below the threshold throughout all the signal period. Information from channels 2 and 3 is totally hidden meaning that the obtained result in terms of AE features can be likely erroneous. The AE system hence stores segments of 200 *ms*-long and considers them as detected hits. These latter are considered to be poorly separated since they do not reflect what was really happening in the material. A further signal processing is then necessary in order to eliminate noise components before performing a hit determination.

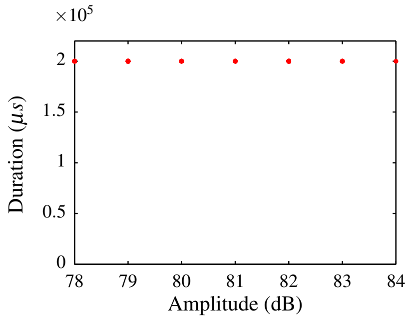

Figure 5 : Duration vs. Amplitude graph of the detected hits from all channels after a PLB under a high noise level.

Figure 6 shows a comparison of the raw and denoised signals of the four channels. As we can see, a considerable progress in terms of improving the signal-to-noise ratio is made, especially for channels 2 and 3. The waveform of the PLB burst is perfectly recovered from the noise. The implemented algorithm allows also the calculation of the AE features, for instance the Duration-Amplitude graphs can be represented in Figure 7 where the saturation of hits at the predefined maximum duration is now eliminated. AE information is greatly revealed and the hits associated to the PLB bursts can be easily identified.

CONCLUSION

The problem of continuous acoustic emission in CFRP composites was addressed in this paper. Continuous signals caused by an in-service like environment are post-processed using a developed algorithm. This latter includes some successive steps allowing the denoising of the raw signals, the hit detection and separation, and the feature extraction. The implemented method was tested on AE signals derived from experimental procedures consisting in a PLB applied on the surface of a composite ring. These tests were carried out under low and high noise levels in order to assess the robustness of the method.

It was found that the developed method was able to improve the signal-to-noise ratio under different working conditions if the denoising parameters had been properly set. After performing the hit determination and the feature extraction, it was found that the calculated features, which had been erroneous due to the noise, became coherent and exploitable. This AE signal method could be applied on realistic transients retrieved for example from a fatigue test on the composite ring in order to assess the reliability of the method. Such test case will be addressed in future works.

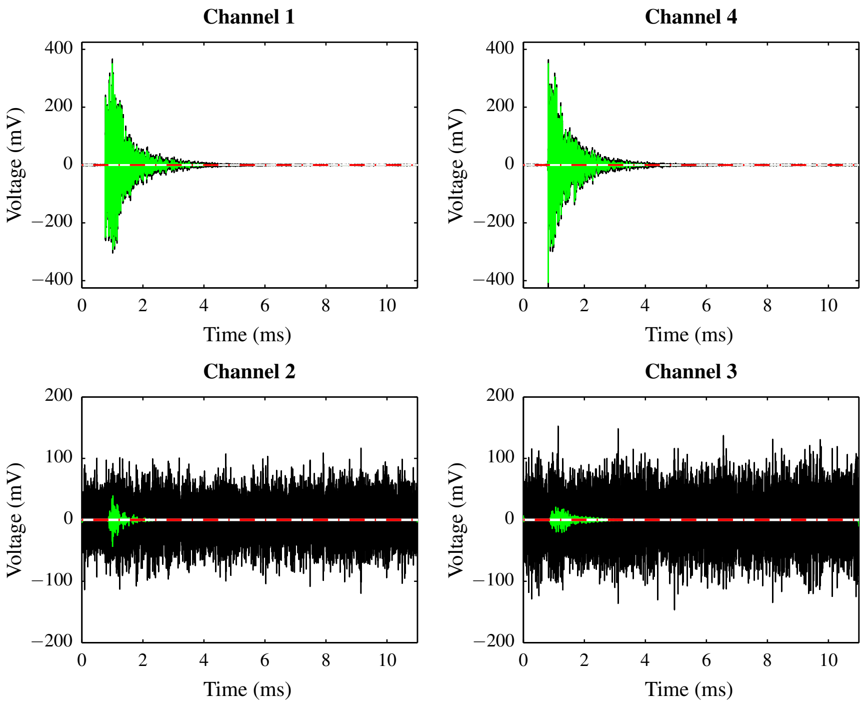

Figure 6 : Comparison of the raw and denoised signals of the four channels after a PLB under a high noise level. (——) Raw signals; (——) denoised signals; and (−·−) threshold level.

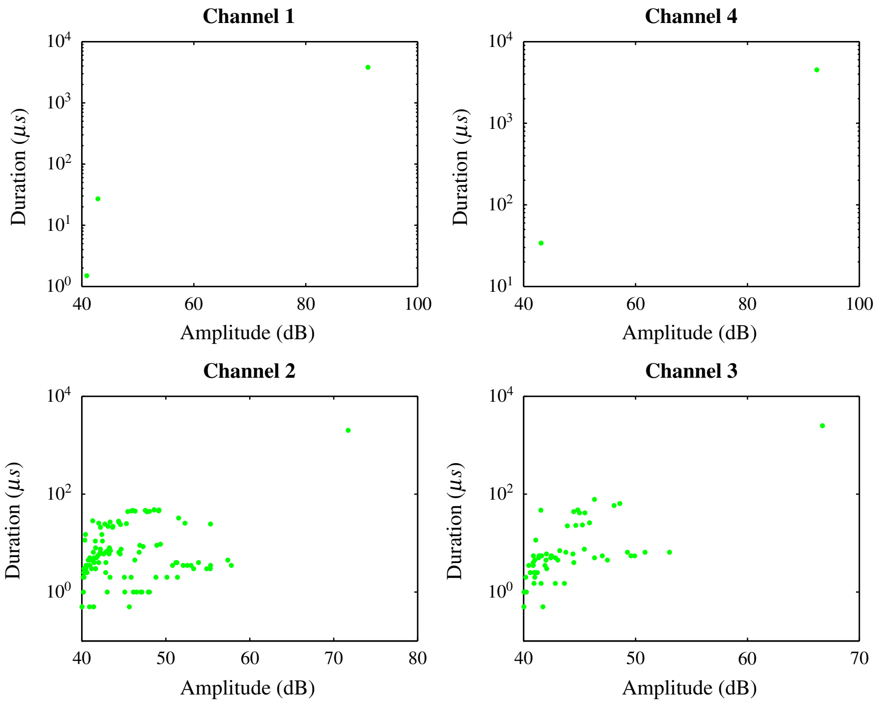

Figure 7 : Duration vs. Amplitude graph of the detected hits after denoising the four signals of the PLB test under a high noise level.

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REFERENCES

[1] J.M. Berthelot and J. Rhazi. Acoustic emission in carbon fibre composites. *Composites Science and Technology*, 37(4):411 – 428, 1990.

[2] R. Unnthorsson, T.P. Runarsson, and M.T. Jonsson. Acoustic emission based fatigue failure criterion for cfrp. *International Journal of Fatigue*, 30(1):11–20, 2008.

[3] M.G.R. Sause and S. Horn. Simulation of acoustic emission in planar carbon fiber reinforced plastic specimens. *Journal of Nondestructive Evaluation*, 29(2):123–142, 2010.

[4] Daniel Gay. *Matériaux composites*. Hermes, 2005.

[5] C.B. Scruby. An introduction to acoustic emission. *Journal of Physics E: Scientific Instruments*, 20(8):946, 1987.

[6] T.J. Holroyd. *The Acoustic Emission & Ultrasonic Monitoring Handbook*. Machine & systems condition monitoring series. Coxmoor Publishing Company, Kingham, Oxford, UK., 2000.

[7] A.P. Mouritz. Non-destructive evaluation of damage accumulation. *Fatigue in Composites, Woodhead Publishing Ltd., Cambridge*, pages 242–266, 2003.

[8] B. Harris. *Fatigue in composites: science and technology of the fatigue response of fibre-reinforced plastics*. Woodhead Publishing, 2003.

[9] M.J.S. Lowe, G. Neau, and M. Deschamps. Properties of guided waves in composite plates, and implications for nde. In *Quantitative Nondestructive Evaluation*, pages 214–221. American Institute of Physics, 2004.

[10] Eaton Corporation. *Noise Control in Hydraulic Systems*, 2002.

[11] Dumitru Baleanu and Handan Aydin. *Advances in wavelet theory and their applications in engineering, physics and technology*. InTech, 2012.

[12] A. Abbate, J. Koay, J. Frankel, S.C. Schroeder, and P. Das. Application of wavelet transform signal processor to ultrasound. In *Ultrasonics Symposium, 1994. Proceedings., 1994 IEEE*, volume 2, pages 1147–1152. IEEE, 1994.

[13] H. Kim and H. Melhem. Damage detection of structures by wavelet analysis. *Engineering Structures*, 26(3):347–362, 2004.

[14] J. Lin and L. Qu. Feature extraction based on morlet wavelet and its application for mechanical fault diagnosis. *Journal of sound and vibration*, 234(1):135–148, 2000.

[15] Y. Wang, Z. He, and Y. Zi. Enhancement of signal denoising and multiple fault signatures detecting in rotating machinery using dual-tree complex wavelet transform. *Mechanical Systems and Signal Processing*, 24(1):119–137, 2010.

[16] Y. Feng, S. Thanagasundram, and F.S. Schlindwein. Discrete wavelet-based thresholding study on acoustic emission signals to detect bearing defect on a rotating machine. In *The Thirteen International Congress of Sound and Vibration. Vienna, Austria*, 2006.

[17] A. Satour, S. Montrésor, M. Bentahar, R. Elguerjouma, and F. Boubenider. Acoustic emission signal denoising to improve damage analysis in glass fibre-reinforced composites. *Nondestructive Testing and Evaluation*, pages 1–15, 2013.

[18] N.N. Hsu and F.R. Breckenridge. Characterization and calibration of acoustic emission sensors. *Materials Evaluation*, 39(1):60–68, 1981.

[19] D. L. Donoho and J. M. Johnstone. Ideal spatial adaptation by wavelet shrinkage. *Biometrika*, 81(3):425–455, 1994.

[20] D. L. Donoho. De-noising by soft-thresholding. *IEEE Transactions on Information Theory*, 41(3):613–627, 1995.

[21] C.U. Grosse and M. Ohtsu. *Acoustic emission testing*. Springer, 2008.