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TOWARDS A BETTER LIFETIME PREDICTION OF COMPOSITE STRUCTURES UNDER IN-SERVICE CONDITIONS: ROBUST AND REAL-TIME PROCESSING OF ACOUSTIC EMISSION TIME-SERIES IN PRESENCE OF DAMAGE ACCUMULATION

Mohamed KHARRAT [1], Emmanuel RAMASSO [2], Dinh Dong DOAN [1,2],
Vincent PLACET [1], Lamine BOUBAKAR [1]
[1]Department of Applied Mechanics
[2]Department of Automatic Control and Micro-Mechatronic Systems
FEMTO-ST Institute–UMR CNRS 6174–UFC/ENSMM/UTBM, 25000, Besançon, France
[1]mohamed.kharrat@femto-st.fr

Abstract. Due to the difficulties encountered to predict the long-term behaviour of composite structures in operating conditions, a real-time monitoring of their integrity is required in order to anticipate catastrophic failures. Although the early detection of crack initiation and propagation is beyond the potential of most non-destructive techniques (NDT), acoustic emission (AE) is one of a limited number of methods that possess the capacity for continuously detecting the occurrence of damage in large composite components or structures. Even if promising and successfully exploited in several industrial fields using commercial systems, AE has not provided at this time an effective NDT tool for composite industry, in particular for mobile structures and in-service applications.

For such applications, the main difficulties are related to the real-time processing of a huge amount of complex AE time-series originating from multiple distributed sensors. One major problem is the discrimination of AE signals generated by the different damage modes from other external AE sources such as electromagnetic and mechanical noises (rubbing and friction) which are mainly generated by the surrounding environment. Another important problem is the processing of continuous and complex AE signals resulting from high AE rates, from the superimposition of transients emitted from different sources and from the distortion induced by damage accumulation.

In this context, we have developed a method able to objectively discriminate with robustness AE signals generated by a specific damage mode from other AE sources in carbon fibre reinforced composite materials submitted to complex loading (multiaxial fatigue). This method includes wavelet transform-based signal processing and unsupervised multivariate pattern recognition of massive AE streaming. Uncertainties on the estimation of clusters are quantified by fusing multiple clusterings. We demonstrate on real cases that the proposed method is able to efficiently process massive AE data, as encountered in operating conditions, and take into account the distortion of the AE signals as well as the evolution of the clusters shape induced by the wave attenuation, anisotropy and damage accumulation in composite materials submitted to cyclic loading.

Introduction

A widespread application of composite materials in lightweight structures can be noted during these recent decades thanks to their superior fatigue resistance compared to traditional engineering materials (steel, aluminium alloys…). In the aerospace industry, a large variety of components that must withstand extreme cyclic loads for long times (aircraft propellers, wings, helicopter rotor blades, rotating machinery…) are increasingly made of composites. When these components are exposed to fatigue load conditions like stress or thermal cycling, damages can develop in form of several mechanisms such as matrix cracking, fibre fracture, debonding, delamination… [1]. The fatigue damage can compromise the mechanical integrity and safety of a composite structure, hence the necessity of its early detection using Non-Destructive Evaluation (NDE) technologies.

Acoustic Emission (AE) is an effective NDE technique able to ensure an *in-situ* monitoring of the structure through a network of distributed sensors, and can be used to detect damages at a very early stage well before the structure becomes completely failed [2]. Among the pros of the AE technique is the ability to monitor damage initiation and accumulation in real-time, which is not possible with most other NDE techniques [3]. However, the prediction of the remaining lifetime of composite structures is still a challenging issue [4, 5, 6]. A reliable lifetime assessment needs a well understanding of the damage mechanisms and kinetics, as well as an efficient real-time signal processing and data analysis able to discriminate the damage-related AE events from other external sources like electromagnetic and mechanical noises (rubbing and friction) which are mainly generated by the surrounding environment. Among the major issues facing an efficient lifetime prediction of composite structures is the processing of continuous and complex AE signals. These latter can be generated with high AE rates, when transients emitted from different sources are superimposed, as well as with damage accumulation that causes waveforms distortion.

Continuous signals consist of multiple overlapping transients emitted from different emission sources [7, 8]. These overlapping transients cannot be distinguished and attributed to their emission sources. Major causes of continuous signals are background noise and rubbing. The noise might sometimes bury relevant information about the integrity of the monitored structures. Most of the commercial parameter-based AE systems employ the conventional technique based on both threshold and timing parameters for hits detection and determination. AE systems can hence treat and interpret erroneously the recorded signals. The footprint of noise on the AE features cannot be neglected, as they are usually determined without an efficient consideration of noise variations that can be superimposed with eventual AE events related to microstructural material changes.

The acoustic signatures of damages may be influenced by several factors. Among the factors of influence that have been relatively well studied in the literature, we can mention: sensors technology and associated electronics [9], the coupling between the sensor and the material [10], the distance between the acoustic source and the sensor [11], the physical properties of the material including material symmetries and wave propagation characteristics (dispersion, attenuation. . .) [12]. The geometry of the specimen is also an important parameter involving the edge effect, the dimensions of specimens, as well as interactions with existing discontinuities (holes, rivets...). These lead to wave dispersions and distortions [13]. Particularly, the effect of damage accumulation during mechanical loading on the AE features could be substantial. It has been demonstrated that the captured waveforms during tests performed on cementitious materials [14] and bearings [15] have been altered by the damage growth and therefore the AE features have been influenced. The acoustic signatures of damages may evolve during the fatigue life of a composite structure. Indeed, the damages emerging in the material would disrupt the wave propagation modes and could therefore contribute to a distortion in the detected transients. The quality and relevance of the hits classification (based on the AE features) could be largely impacted leading to an erroneous structural health assessment.

In this paper, the aforementioned challenging issues encountered in AE data processing and analysis are emphasized by performing experimental tests. A developed numerical method dealing with these issues is thereafter presented. It is able to objectively discriminate with robustness AE signals generated by a specific damage mode from other AE sources in carbon fibre reinforced composite (CFRP) materials submitted to complex loading.

1. Challenging issues on AE data processing and analysis

1.1. Continuous emission in high AE activity systems

In order to illustrate the issue, an experimental procedure is performed. A tensile test with a high loading rate is carried out on an intact CFRP specimen until its total failure under a high ambient noise created by the hydraulic system of the tensile machine. The high loading rate engenders a high AE rate. This configuration simulates in-service-like cyclic loading under severe working conditions and results in complex experimental signals where continuous signals and eventual damage-related transients could be superimposed. The test specimen is a 1.5mm thick composite ring with an outer diameter of 124mm and a width of 16mm. It is mounted on a tensile testing machine using two clamping jaws (two half-cylinders) as illustrated in Figure 1. These two jaws are not in contact during the test, so the wave propagation is guided only by the composite ring. Four wide-band AE sensors of Micro80-type (Mistras Group Ltd.) 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. The hydraulic system of the testing machine 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. The test consists in applying an increasing tensile force (a ramp function) on the composite ring starting from 0N to 60kN with a speed of 15kN/s until the total failure.

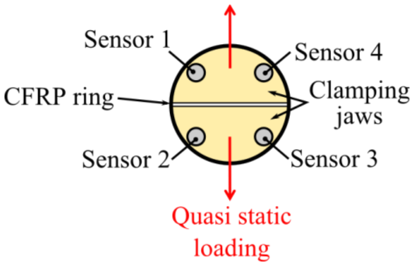
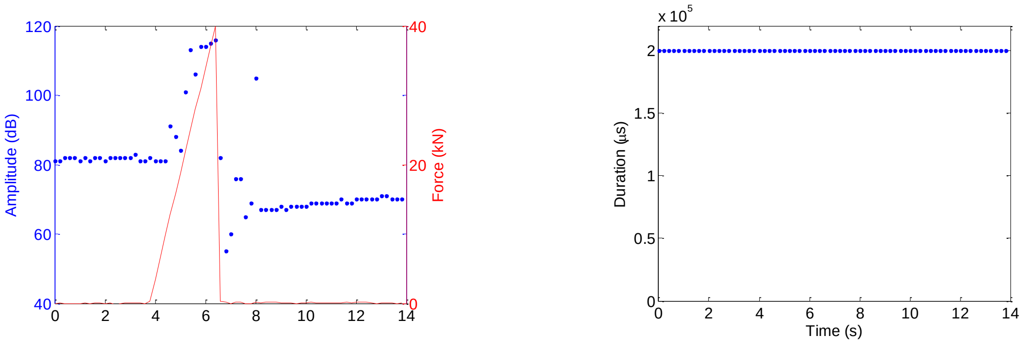


Figure 1 Test configuration.

Some AE features calculated for channel 2 are retrieved from the data acquisition file of the AE system. Figure 2(a) shows the amplitude of the detected hits obtained using the AE system and the applied force exerted by the machine on the specimen over the time of test. As we can note, the amplitude increases with loading that begins rising a little before the 4th second; then it falls again when the force tumbles down shortly before the 7th second with the complete failure of the ring. Hits' durations are represented as a function of time in Figure 2(b). Patently, the durations of all detected hits are equal to the maximum duration predefined in the system (200ms). This is a total saturation of the AE system. The AE system has considered 200ms-long signal segments as detected hits because the amplitude is maintained above the threshold during a certain period. These hits are thus poorly separated. This potentially erroneous hit separation may be caused either by noise or by damage growth and accumulation in the material leading to a high AE activity. This phenomenon is quite significant in channels 2 and 3 as they are more impacted by the generated noise. Increasing the threshold would help to avoid saturations but this might eliminate low amplitude hits.



(a) (b)

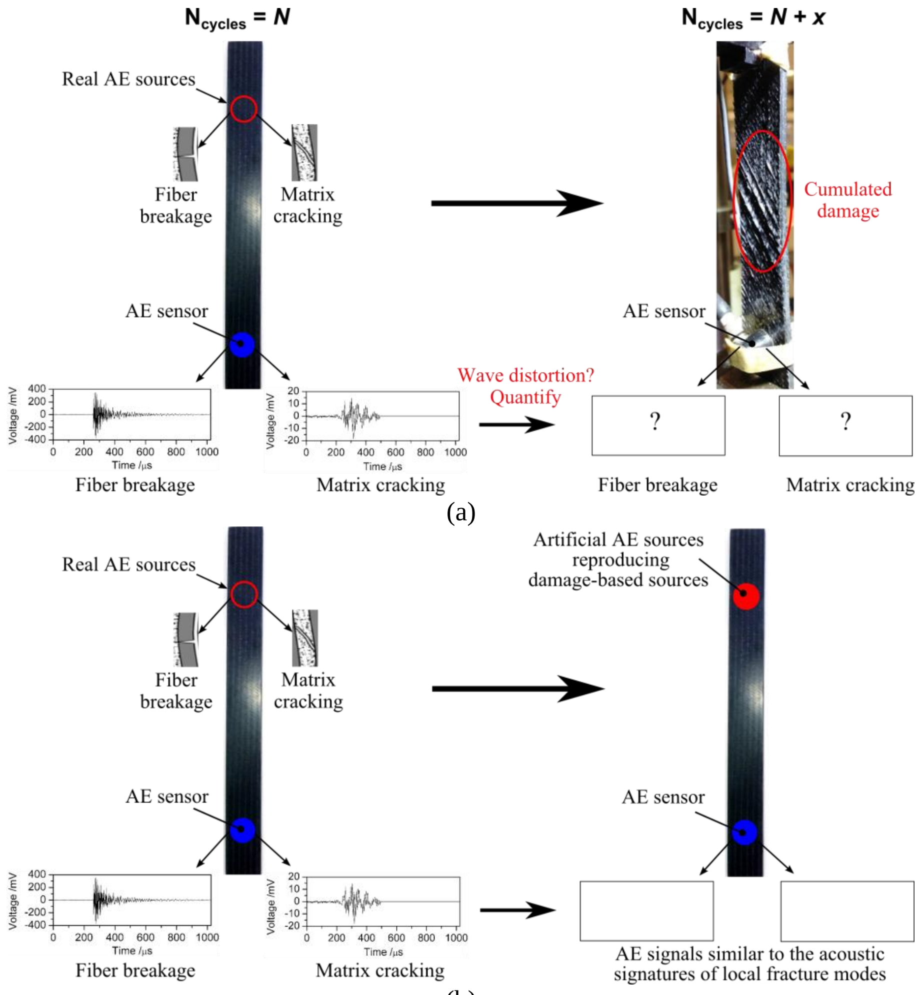
Figure 2 A selection of AE features over time retrieved from the channel 2 data acquired during the tensile test: (a) Amplitude and force; (b) Duration.

1.2. Distortion of the AE waveforms with damage accumulation

The eventual evolution of the AE waveforms during a fatigue test is discussed. The principle of the study is illustrated in Figure 3. An experimental procedure is conducted by creating artificial acoustic sources in order to reproduce and simulate different damage AE sources. An ultrasonic transducer and a Pencil Lead Break (PLB) are used as artificial AE sources in CFRP specimens undergoing cycling tensile fatigue tests. An AE sensor is used to collect the signals. An appropriate algorithm is then employed to extract the hits and determine the AE-features. Their evolutions with respect to the damage development are finally examined.

The tested material is a ±45° angle biaxial carbon stitched with textured polyester reinforced epoxy resin. The specimens are composed of eight plies with dimensions 250×25×3.5mm. They are subjected to tensile-tensile fatigue tests at a loading level of 70% of the ultimate tensile strength (UTS). The profile of solicitation is sinusoidal with a frequency of 5 Hz and a stress ratio $R = 0.1$ (where $R = \sigma_{min}/\sigma_{max}$). Two extensometers were mounted to measure the longitudinal and transverse strains (gauge lengths equal to 50mm and 12.5 mm respectively). In order to generate acoustic signals at different health states of the material, the cyclic loading is interrupted several times during the tests. The input signal of the transmitter transducer is created using a waveform generator (Tabor Electronics 5064, 100MS/s) and a power amplifier (Tabor Electronics 9100 A, with a fixed gain of 50). It is an impulse-like signal that was optimized in terms of its shape, duration and amplitude to obtain transient bursts at the sensor level similar to those generated by a PLB (see Figure 4). All the sensors used here are of Micro80 type.

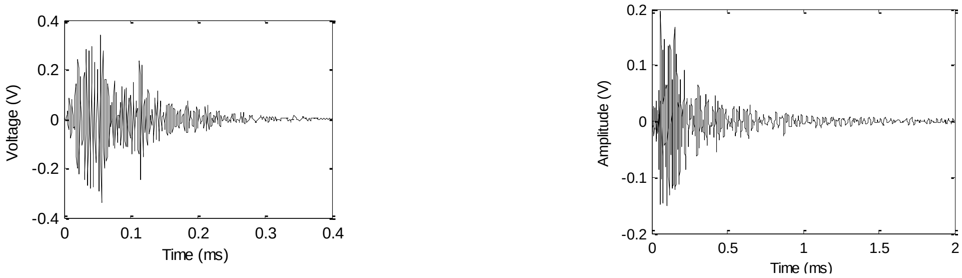
It can be remarked that the shapes of the AE signals are noticeably distorted and the frequency spectra exhibit an evolution under the effect of cumulated damage when using both artificial AE sources. The AE-features calculated from the detected hits evolve during the damage development, as shown in Figure 5 for the case of the transmitter transducer. This evolution could considerably affect the identification of the natural clusters/classes using the pattern recognition tools, as it is based on the calculated AE features.



(a)

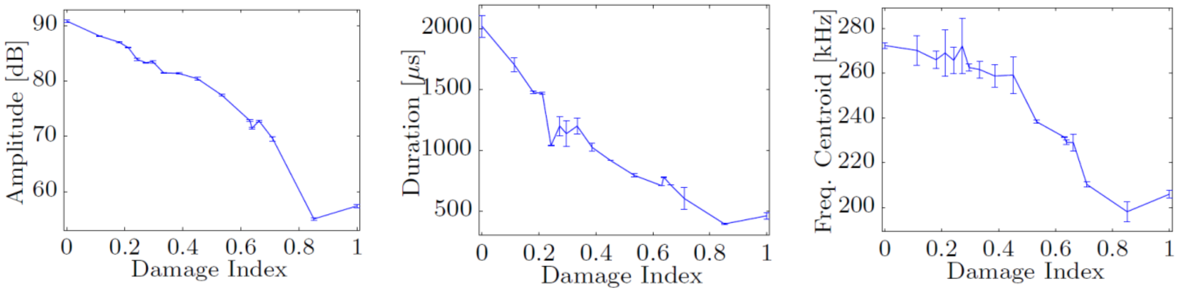
(b)

Figure 3 Purpose of the study: (a) potential evolution of the acoustic signatures of local fracture mechanisms during cyclic loading; and (b) the proposed methodology and experimental procedure for verification.



(a) (b)

Figure 4 Artificial acoustic sources reproduced by (a) an ultrasonic transmitter transducer and (b) PLB detected by the AE sensor mounted on the same surface of a healthy composite specimen.



(a) (b) (c)

Figure 5 Evolution of the AE-features with cumulated damage when using a transmitter transducer as AE source.

2. Development of an AE signal processing and data analysis approach

The proposed method consists in successive steps, as schematized in Figure 6, in which the continuous emission signal is post-treated after being recorded entirely. The signal is either processed one shot or 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 Discrete Wavelet Transform (DWT). The choice of the appropriate denoising parameters is crucial in order to obtain a high signal-to-noise ratio. Afterward, the signal or segment is swept in order to determine potential hits. The AE features are thereafter computed and stored. The final step is data clustering, which involves grouping the AE data into classes or clusters representing the possible AE sources.

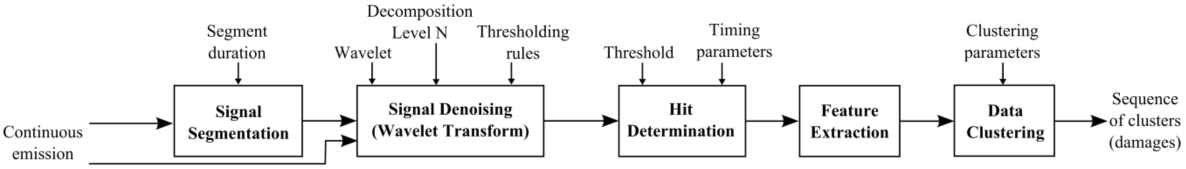
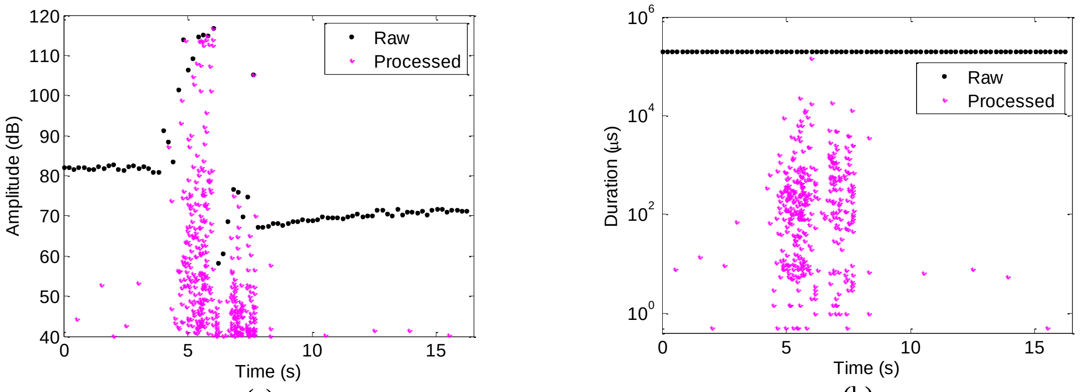


Figure 6 Principle of the AE signal processing method.

In order to overcome the problem of loading heavy signal files and trying to eliminate completely the hits saturation, signal segmentation is adopted. The signal to be processed is thus divided into short segments with equal durations of 0.5s. This value is chosen so that the number of samples in each segment is easily loaded and handled by the computer. Then, each signal segment is successively denoised and eventual hits are determined. This strategy has the advantage of surmounting the limitation of the computer memory since the entire signal is now loaded segment by segment and not a single shot. For the test mentioned in section 1.1, the denoising process is performed using the Daubechies wavelet ’db45’, 7 decomposition levels, a soft thresholding with a selection rule of the universal threshold ’sqtwolog’, and considering a non-white noise model.

Figure 7 shows a comparison between the hits detected by the AE system method on the raw signal and those obtained by the proposed approach. The most important ascertainment is that the saturation phenomenon is now eliminated. All the separated hits have durations less than the pre-defined maximum duration. The number of detected hits before the start of the loading is greatly reduced. In fact, by segmenting each signal the denoising procedure is improved. The noise estimation is performed for each signal segment independently of the other segments, so that the denoising parameters are updated and adjusted for each segment. In fact, an appropriate hit detection algorithm leads to a better identification of natural clusters in AEs and improves the interpretation of damage mechanisms. A further explanation of the findings can be found in previous publications of the authors [16, 17]. The AE data obtained after the above-mentioned denoising procedure is analyzed by the pattern recognition approach proposed by Ramasso et al. [18]. A number of clusters K=7 is found to be the optimal value (based on the NMI criterion). Figure 15 presents the obtained sequences of clusters, where the vertical axis corresponds to the decimal logarithm of the cumulative occurrence of AE hits in a given cluster (called CSCA). These graphs allow locating the time of occurrence of each cluster, and following the temporal evolution of its activity. A first cluster starts at the same time as the AE acquisition (without loading) which is coherent with the activation of an AE source related to the ’structureborne’ and ’fluidborne’ noises. This cluster represents 62% of the total number of hits and may regroup those associated to external emission sources as well as other meaningless hits. Clusters 2, 3 and 4 start at the same time as the loading and are activated throughout the test. These clusters are thus associated to the activation of AE sources related for example to the friction between the specimen and the clamping-jaws. This friction is also observed after the specimen failure. The remaining clusters 5, 6 and 7 are probably associated to the material damage mechanisms as they appear during the specimen loading period. It can be concluded that the proposed algorithm leads to a better identification of the natural clusters in acoustic emissions and improves the interpretation of damage mechanisms.



(a) (b)

Figure 7 Comparison between the detected hits in the raw signal of channel 2 and those obtained by the proposed approach (signal segmentation and denoising using the DWT). (a) Amplitude and (b) duration over the acquisition time.

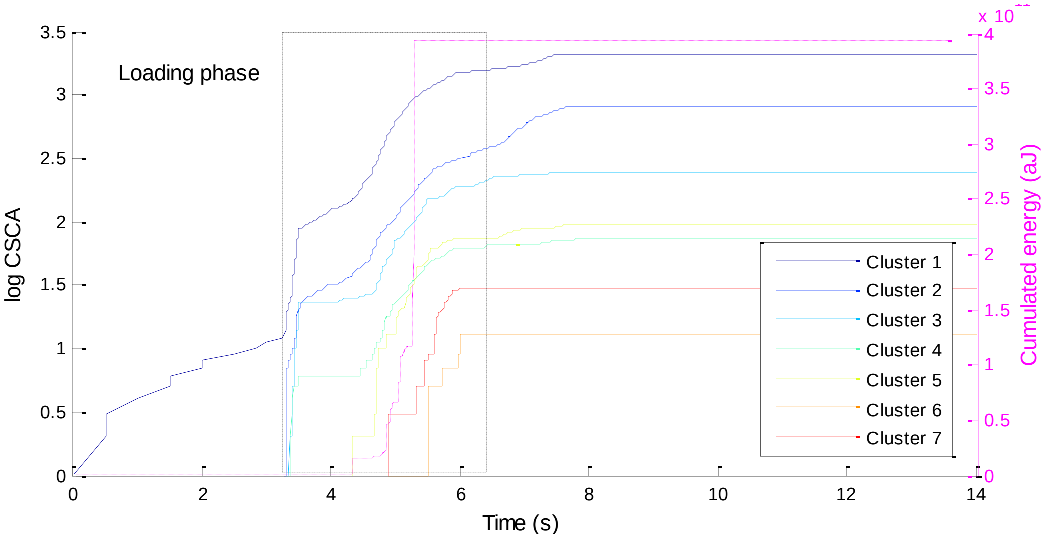


Figure 8 Clustering sequences obtained using the proposed approach.

Conclusion

In this paper, the issues frequently encountered in high AE activity systems are discussed. They are mainly related to the real-time processing of a huge amount of complex AE time-series. The discrimination of AE signals engendered by damages from the other external AE sources. The distortion of the waveforms under the effect of damage accumulation is also another problem as it impacts the pattern recognition. An approach was developed by the authors in order to identify with robustness AE signals generated by damage modes.

It was demonstrated on real cases that the proposed approach is able to efficiently process massive AE data, as encountered in operating conditions. Regarding the problem of the AE waveforms evolving during the damage accumulation, it would be of interest to develop data clustering/classification algorithms able to adapt the form of clusters along different directions in the feature spaces.

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