

Article

Towards Acousto-Ultrasonic Inspection of Cables Within Their Anchor Bases for Suspension Bridges

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Featured Application

This work contributes to the development of an acousto-ultrasonic inspection method for detecting defects in bridge cables embedded within their anchor bases.

Abstract

This study proposes an approach based on an acousto-ultrasonic method and feature-based analysis to assess the condition of cables within their anchor bases. Experimental tests were performed on several model anchor configurations, including a healthy reference (REF-1) and different degraded configurations (namely DEF-1Z, DEF-2Z, DEF-W), in order to investigate the influence of the number of broken wires on the recorded signal. The acquired signals were characterised using acoustic emission features such as amplitude, energy, duration, counts, and centroid frequency. Z-score normalisation was applied according to two strategies—joint normalisation using a reference anchor base, and reference-free normalisation—in order to better reflect in situ inspection conditions. The objective is to discriminate between healthy and degraded cable states within anchor bases, first with a reference-based approach and then without any reference. The results show that several features have strong discriminative potential. In addition, the reference-free results show good agreement between sensor positions and degraded areas, confirming the localisation of the damage. Overall, this approach appears promising for future in situ applications.

Keywords: bridge; cables; acousto-ultrasonic; anchor base; defect; detection



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1. Introduction

Many civil engineering structures are ageing, with some dating back to the nineteenth century. Cable-supported bridges, including suspension and cable-stayed bridges, represent a significant part of this ageing infrastructure heritage [1,2]. To ensure their structural integrity, each component of these structures must be inspected regularly. However, the section of the cable located inside the anchor base remains a critical zone that is difficult to access using conventional non-destructive testing (NDT) methods [3]. This area is exposed to several degradation mechanisms, including corrosion caused by water stagnation at the bottom of the socket and fretting fatigue between cable wires at the entrance of the anchor base. This phenomenon results from repeated small-amplitude relative movements between adjacent wires or socket, induced by variations in cable tension and structural vibrations, which generate localised wear and may promote fatigue crack initiation [4–7].

An anchor base consists of a metallic socket into which the cable is inserted; the wires are first spread out to form a bun and are then immobilised using a zinc-based fusible material [8]. The complex geometry of this assembly, combined with high wave attenuation, makes the inspection of cables particularly challenging.

In the context of ageing infrastructures, the use of non-destructive testing methods has therefore become essential for monitoring cables and their anchorage systems. In cable-supported structures, different degradation mechanisms may affect the mechanical integrity of the strands, including corrosion, fretting fatigue, and wire breaks [3–6]. These forms of damage are especially critical in anchor bases, where accessibility is severely limited and where visual or localised inspections become impossible. In this context, several NDT approaches have been investigated in order to improve structural diagnosis and maintenance strategies. Among these approaches, acoustic emission (AE) has been widely studied for the detection of wire breaks and the monitoring of damage evolution in cables. Previous review work has already highlighted the potential of this technique for monitoring metallic cables [9], and several subsequent studies have confirmed its ability to detect the presence of broken wires in bridge cables [10]. AE thus constitutes a relevant passive method for capturing events related to active structural damage, particularly when wire breaks or damage evolution generate measurable transient emissions. However, this characteristic also makes it a complex technique to implement for the real-time inspection of cables within anchor bases. In parallel, guided ultrasonic waves have shown strong potential for the inspection of complex wire structures and anchorage zones in prestressed bridges. Some studies have proposed the use of guided waves to detect corrosion in the anchorage zones of parallel-wire cables [11], while others have developed approaches adapted to the inspection of multi-strand cables [12]. Recent reviews on detection methods applied to metallic cables also emphasise the relevance of ultrasonic techniques, combined with advanced signal processing methods, for the inspection of anchorage systems [13]. More broadly, Kurz et al. [14] showed that NDT methods are essential for the condition-based maintenance of cables, strands, and prestressed elements, while also highlighting practical limitations encountered on in situ structures, such as accessibility, attenuation, and geometric heterogeneity. Recent studies have also shown that partial structural models can simplify the identification of damage to steel bridges whilst maintaining a satisfactory level of accuracy [15]. Furthermore, the reliability of the diagnosis depends heavily on the location of the sensors, with measurements taken in areas susceptible to damage providing more accurate identification results [16].

Other families of methods have also been explored. Magnetic methods, particularly those based on magnetic flux leakage, have proved effective for detecting wire breaks in accessible sections of cables [17,18]. They are particularly well suited to identify metallic discontinuities or cross-sectional losses, but provide more limited information on the global condition of the anchorage system. In addition, vibration-based approaches coupled with statistical models have recently been proposed to evaluate the nonlinear behaviour of prestressed anchorage systems and to indirectly estimate their residual strength [19]. Recent developments also show a growing interest in approaches based on advanced signal processing and artificial intelligence applied to ultrasonic NDT. For example, Han et al. [20] showed that the combination of non-destructive testing and neural networks can be used to assess the degree of corrosion in bolt-type anchorage elements. Other studies have used principal component analysis, optimised decomposition methods, or deep neural networks to improve the identification and classification of defects in anchorage or bolting systems, including under noisy conditions [21–24]. However, these studies mainly concern bolts, geotechnical anchors, reinforcing bars, or resin-based systems rather than bridge cables

embedded in metallic anchor bases, which limits the direct transposition of their findings to the case of civil engineering cable anchor bases.

More specifically, in anchor-base zones, Kharrat and Gaillet [25] highlighted the complementary value of conventional ultrasonic testing (UT) and acousto-ultrasonic (AU) testing. Their work showed that UT is particularly well suited for locating relatively localised defects, whereas AU appears more relevant for providing a more global assessment of the structural condition of the anchor area. This distinction is important in the case of cables anchored inside their bases, where the geometry is complex, access is limited, and several damage mechanisms may interact, such as defects in the filler material, broken wires close to the base entry, or local loss of cohesion at the cable/anchor base interface. The acousto-ultrasonic technique is based on the combination of ultrasonic and acoustic emission principles [26,27]. The process involves generating a controlled ultrasonic wave within the structure and then analysing the received waves using features/descriptors extracted from the received signal. Unlike approaches based solely on time-of-flight measurements, this method makes it possible to characterise global modifications in signals related to attenuation, dispersion, or changes in frequency content induced by damage. This approach has already been investigated in various fields, including aeronautics [28] and civil engineering [29–33]. In civil engineering, several studies have shown that AU is capable of detecting different types of defects in bonded assemblies used for structural strengthening. Composite plates bonded to steel or concrete have notably been investigated in the presence of defects such as voids, kissing bonds, or poorly cured adhesive zones [31,32]. The analysis generally relies on the extraction of signal descriptors combined with dimensionality reduction tools, such as principal component analysis, and supervised learning methods to identify the damage state [31–33]. These results show that the acousto-ultrasonic approach is well suited to complex and attenuative media, in which damage modifies the overall wave propagation. The AU technique is therefore of particular interest for the inspection of cables within their anchor bases. The cable/anchor base interface is difficult to access, and conventional ultrasonic methods quickly reach their limitations. The most recent studies devoted to this issue have confirmed the feasibility of applying AU to bridge cables inside their anchor bases [25], and have shown the value of using model anchor bases containing controlled defects in order to better understand the influence of different types of degradation on the measured signals. Thus, the state of the art shows that AE, magnetic methods, guided ultrasonics, and vibration-based approaches each provide useful but only partial information on the condition of cables and their anchorage systems. AE is particularly suitable for the detection of active damage events [10–12], magnetic methods for highlighting broken wires [17,18], and guided ultrasonics for the inspection of inaccessible or complex zones [13–16]. AU, by contrast, appears to be a particularly promising approach, as it enables a global assessment of the structural condition of anchorage zones through the analysis of signal modifications [25–27]. Nevertheless, its application to cables within anchor bases still raises several scientific and experimental challenges, particularly with regard to measurement repeatability, signal variability, significant attenuation, and the physical interpretation of the extracted features.

This article presents research on the use of the acousto-ultrasonic technique applied to model anchor bases designed in the laboratory, the advantage of working with a model anchor base is that it provides a reference condition corresponding to an undamaged cable, which can be compared with anchors where the cable has been deliberately damaged. This approach cannot be directly applied in the field, as the condition of the cables within a bridge's anchor bases cannot be known. It is therefore not possible to establish a baseline condition allowing for a reliable comparison with certainty. The aim is to determine whether the emitted signals are modified depending on the position of the sensors along

the cable, in order to detect damaged areas. As a first step, the analysis is carried out using both a reference anchor base and a damaged anchor base in order to establish criteria for discriminating acoustic emission features. In a second step, the reference state is no longer considered, and only the data from a single anchor base are analysed in order to validate the method on model anchor bases. In parallel, the ability of the technique to assess defect severity is investigated by comparing data from several degraded cables affected by different types of damage.

2. Model Anchor Bases

In order to develop and validate the acousto-ultrasonic protocol, several model anchor bases were designed and manufactured. These anchor bases are designed to reproduce the real geometry of the anchoring systems used on suspension bridges. The selected geometry corresponds to anchor bases used for galvanised multilayer steel cables without continuous external protection. These anchorage systems are commonly found on suspension bridges and on certain cable-stayed bridges, where they are located at the cable ends. The defect configurations were selected on the basis of preliminary observations made during the opening of several anchor bases recovered from real structures. Damage was mainly observed in the outer cable layers, with broken wires located in the transition zone between the cable entrance and the section embedded in the fusible material. The production of the model anchor bases follows the main stages of the industrial process (Figure 1). The end of the multi-layer cable (low-alloy steel) is then first flared to form a cable head ('bun') (Figure 1a). Once the bun has been formed, the cable is positioned vertically and a steel socket is inserted to match the geometry of the cable head (Figure 1b). Zinc is then poured into the socket; after cooling and solidification, the zinc provides mechanical support for the bun and anchors the cable wires (Figure 1c). The zinc provides mechanical support for the bun and anchors the cable wires (Figure 1c).

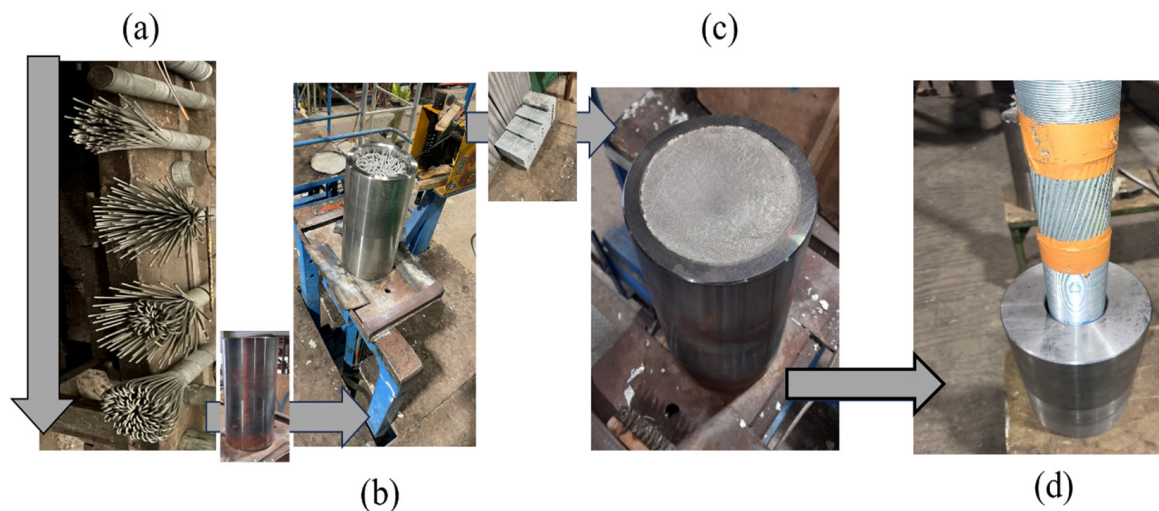


Figure 1. Process for anchor base: (a) creating a bun with the end of the cable, (b) placing the socket around the bun, (c) pouring zinc into the socket, (d) complete anchor base.

The dimensions of the anchor base and cable are shown in Figure 2. The steel socket and the multi-layer cable are 348 mm and 1000 mm long, respectively, with diameters of 200 mm for the socket and 73.66 mm for the cable. The cable consists of 126 individual wires, each with a diameter of 5.6 mm. After the zinc had solidified, the socket was removed by applying a force to the end of the cable and to the edges of the anchor base in order to extract the steel sleeve and subsequently introduce controlled damage into the red-marked area (Figure 2).

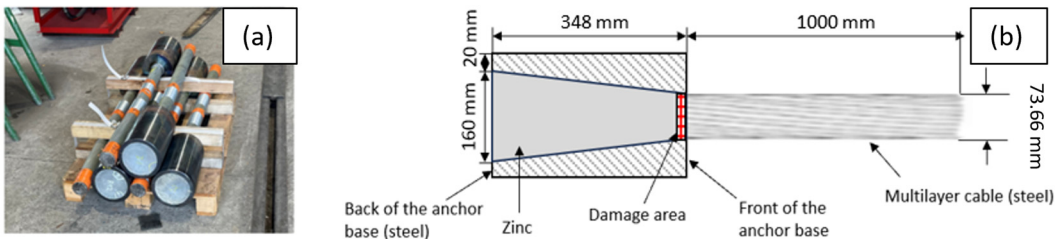


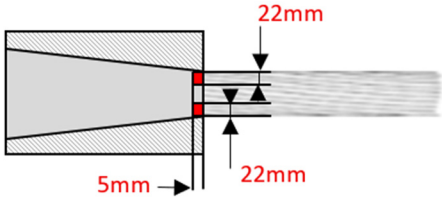
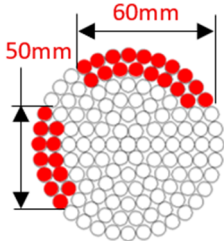
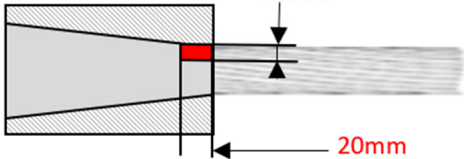
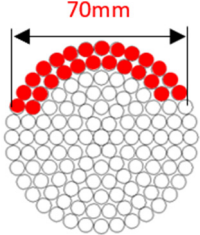
Figure 2. (a) Set of standard cable anchor bases; (b) cross-sectional view of a cable anchor base showing the geometries of the anchor and the cable, as well as the area where degradation occurs.

Once the zinc had cooled completely (Figure 1c), the socket was removed in order to check that the fusible material had penetrated and distributed correctly around the cable. Defects were then introduced into the cable, after which the sleeve was repositioned around the solidified zinc block until mechanical contact was re-established at its original stop. Although reassembling the socket may slightly change the local mechanical coupling, this effect should be limited as the excitation is applied directly to the zinc, which remains in constant contact with the cable wires, whilst the steel wires act as waveguides for signal propagation. The schematics presented in Table 1 illustrate the four model anchor base types investigated in this study, while the schematic cross-sectional views indicate the location and extent of broken wires for each degradation scenario. Several types of degradation have been introduced in the cables of the model bases. The defects consist of broken wires distributed in different configurations. The REF-1 base has no defects in the cable and acts as reference. The DEF-1Z and DEF-2Z bases have broken wires affecting the first two to three layers of the cable (25 and 22 mm deep, respectively), with a degradation width of approximately 5 mm; the extent of this degradation is illustrated in Table 1. The DEF-W anchor shows greater degradation in width (approximately 20 mm), also affecting the first two layers of wires to a depth of approximately 17 mm. The geometry of the defects was defined in such a way as to assess the technique’s sensitivity to various types of damage, with different shapes and lengths. The percentage of broken wires was determined with reference to the residual strength of a suspension bridge cable, for which a failure is generally considered to occur when 45% of the wires are broken. In this study, the DEF-1Z corresponds to the highest severity level, followed by the DEF-2Z, whilst the DEF-W represents the least severe configuration.

Table 1. Abbreviations and description of the model anchor bases. Broken wires are represented by red rectangles and red circles in the cross-sectional and front views.

Abbr.	Description	Cross-Section View of Anchor Base	Front View of the Cable
REF-1	Reference anchor base		
DEF-1Z	Damaged anchor base with significant broken wires (33% of the wires in the cable are broken)		

Table 1. Cont.

Abbr.	Description	Cross-Section View of Anchor Base	Front View of the Cable
DEF-2Z	Damaged anchor base on both sides of the cable (24% of the wires in the cable are broken)		
DEF-W	Damaged anchor base with in-depth damage inside socket (21% of the wires in the cable are broken)		

Model bases provide a relevant experimental basis for optimising the measurement protocol, analysing the sensitivity of features and assessing the influence of sensor positioning. This experimental approach offers a controlled-state cable configuration that cannot be obtained in situ.

3. Acousto-Ultrasonic Setup and Methodology

3.1. Experimental Setup for Acousto-Ultrasonic Testing

The experimental setup is based on the generation of an ultrasonic signal using an ARB1410 card as a waveform generator (from MISTRAS France Group). The acquisition and propagation parameters were defined on the basis of preliminary tests carried out on simplified configurations, including measurements performed on steel cylinders with a diameter close to that of the cable, as well as sensor-to-sensor tests. The choice of sensors was also guided by these initial tests. The emission signal consists of a modulated sinusoidal waveform with an amplitude of 100 dB, rise and fall times of 100 μs and a centroid frequency of 320 kHz. The modulated sinusoidal waveform was selected following preliminary sensor-to-sensor tests, as it produced a received signal close to the prescribed excitation with limited distortion, unlike square, triangular, and sawtooth waveforms. It therefore provided a more controlled and reproducible excitation for the analysis of signal. The waves are emitted at a repetition frequency of 0.5 Hz over a duration of 60 s. The signal is injected into the anchor base via a piezoelectric transmitter sensor positioned at its end. This sensor is a Micro80 transducer, with a resonance frequency of approximately 320 kHz, ensuring efficient transmission in this frequency range. The waves are received by four wideband piezoelectric sensors (WD type from MISTRAS Group) arranged at 90° intervals around the cable (Figure 3). The coupling between the sensors and the cable (or the end of the anchor base) is achieved using silicone grease to ensure acoustic impedance matching, while their positioning is ensured by magnetic holders manufactured using 3D printing. The received signals are first amplified using 2/4/6 preamplifiers set to a gain of 40 dB, with filtering in the 20–1000 kHz range, in order to improve the signal-to-noise ratio. A detection threshold of 35 dB was adopted for the inspection. The signals are then digitised and recorded using the Express-8 acquisition system (Mistras), enabling the acquisition and analysis of acoustic emission data associated with ultrasonic wave propagation within the anchor base (Figure 3). The receiving sensors are positioned 100 mm from the anchor

base in order to replicate on-site inspection conditions as closely as possible. This assembly makes it difficult to gain direct access to the area where the cable enters the anchor. In addition, the receiving sensor is positioned at the mid-height of the filler material in order to promote wave propagation through the cable wires and to obtain a representative response from the anchored zone.

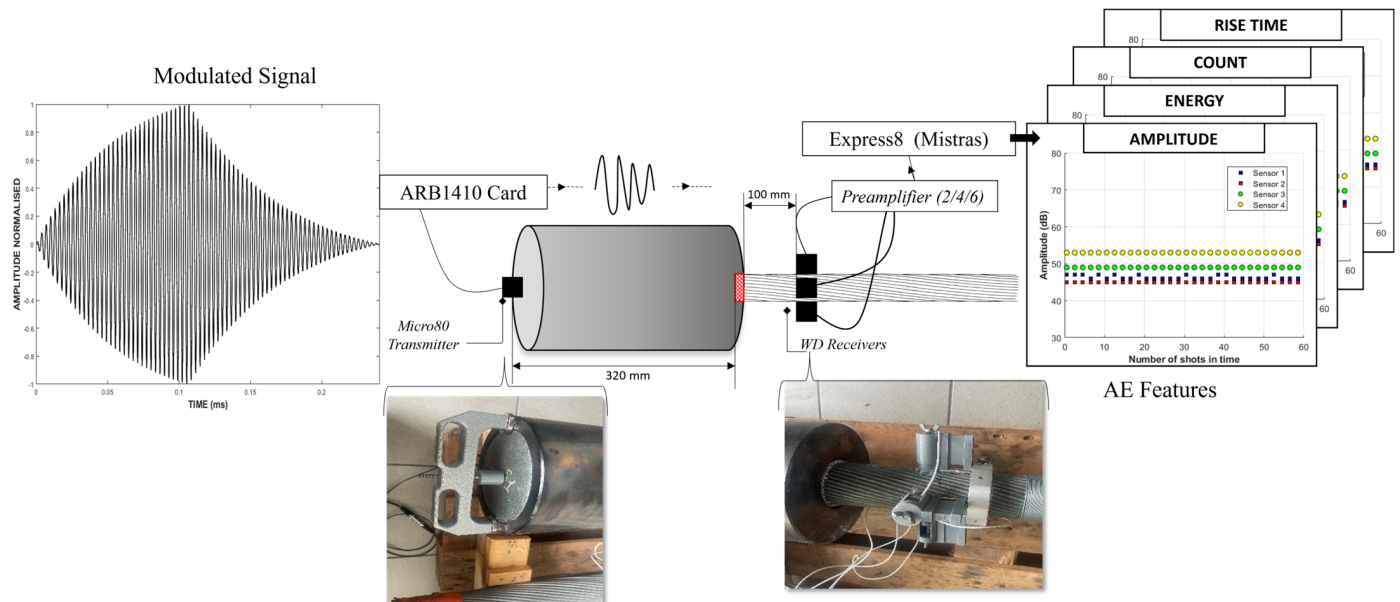


Figure 3. Experimental device for acousto-ultrasonic testing of model anchor bases, including excitation signal generation, sensor layout and signal acquisition process.

Figure 4 shows the location of sensors on the cables for the different model anchor bases. On the REF-1 anchor base, all sensors are located along the extension of a (healthy) area of the cable. In contrast, for the damaged anchor bases (DEF-1Z, DEF-2Z and DEF-W), sensors 1 and 2 are positioned along the extension of the broken wires, whereas sensors 3 and 4 are placed on undamaged areas of the cable.

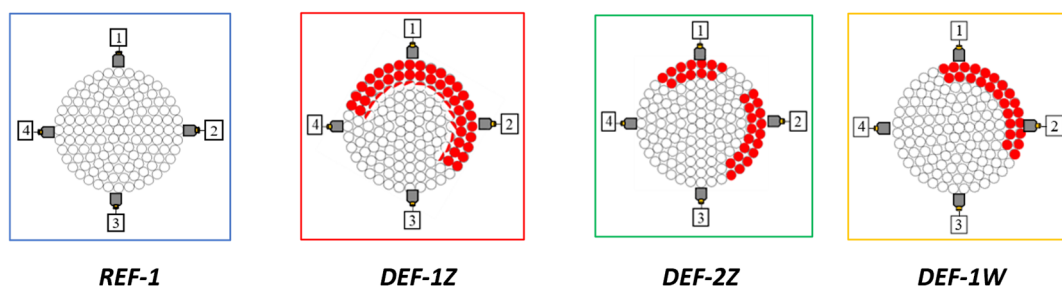


Figure 4. Location of sensors (1, 2, 3 and 4) on model anchor bases.

In order to verify the correct installation of the emitting sensors, an Auto Sensor Test (AST) was systematically performed. In addition, five assembly and disassembly cycles of the emitting and receiving sensors were carried out in order to assess measurement repeatability. The results showed only insignificant variations in the analysed parameters, thereby confirming the good reproducibility of the experimental protocol.

3.2. Methodology for Signal Processing and Feature Extraction

The analysis of the collected data is carried out using two complementary approaches. First, the signals obtained by the sensors are examined and compared in order to identify

differences in both the time and frequency domains. Second, the analysis focuses on the features extracted from the signals, both in the time and frequency domains.

3.2.1. Waveform Analysis

In the time domain, the signals were initially analysed in their raw form after extraction from the Express-8 acquisition system. In the frequency domain, the analysis was based on the power spectral density (PSD) of the signals. The PSD was estimated using the Welch method [34,35] which reduces the variance of the spectral estimate. Each time signal was divided into 256-sample segments, weighted with a Hamming window and overlapped by 50%. The spectra were expressed in dB/Hz and represented as a function of frequency over the useful bandwidth from 0 to 1000 kHz. This representation allows comparison between different anchor bases and helps identify variations in the overall spectral level, together with the appearance or shift in dominant frequency peaks.

3.2.2. Analysis of AE Features

The data are analysed using features that characterise the signal in both frequency/time domains. The features used are described in Table 2.

Table 2. Features for data analysis.

Features	Symbols	Unit	Definition
Amplitude	AMP	dB	The peak amplitude of the signal, calculated from the amplitude (V) at the output of the chain.
Energy	ENER	v.µs	The integral of the rectified voltage signal over the duration of the AE signal.
Duration	DURATION	µs	The time elapsed between the first and last instances in which a signal's threshold was exceeded.
Absolute Energy	ABS-ENERGY	attoJ	The integral of the square of the signal voltage over its duration.
Centroid Frequency	C-FRQ	kHz	The frequency centroid of the frequency spectrum obtained by Fourier transform.
Number of counts	COUNTS		Number of times the threshold was crossed during the duration of the signal.
Signal Strength	SIG-STRNGTH	pV.s	The area under the signal envelope
Rise time	RT	µs	The time between the AE signal start and the peak amplitude of the AE signal.
Counts to Peak	PCNTS		The measure of the number of AE Counts between the AE signal start and the peak amplitude of the AE signal.
Peak frequency	P-FRQ	kHz	The maximum frequency of the peak in the Fourier transform of the signal.

Several studies have investigated different normalisation methods [13]. In this study, Z-score normalisation (in an interval from -3 to 3) was selected, as it allows the data to be centred and scaled. The first approach consists of combining data from a reference anchor base with those from a degraded anchor base (i). The features extracted from the signals acquired on both anchor bases are paired and jointly normalised using a Z-score. After this step, the data are separated, by sensor, in order to enable a comparative analysis between the reference anchor base and damaged ones (Figure 5).

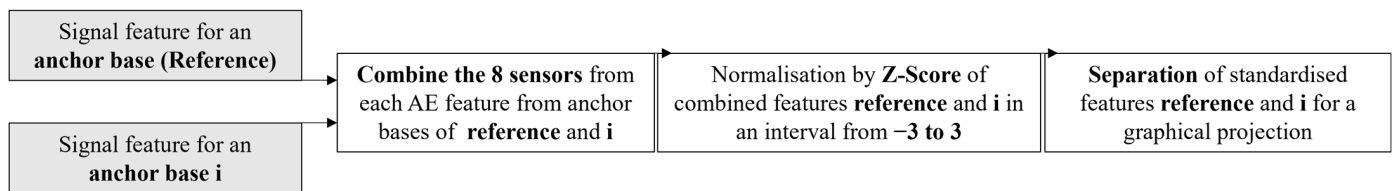


Figure 5. Z-score normalisation process applied to a reference anchor base and a degraded anchor base (i) by combining the data from all 8 sensors.

Based on this approach, decision criteria have been defined to distinguish sound anchorages from degraded ones based on sensor responses. The second approach involves applying Z-score normalisation directly to data from a single anchor base, without introducing an external reference. This method allows for the analysis of internal variations within a single model anchor base database and enables the comparison of sensor responses for a given configuration (Figure 6). It was adopted to determine whether the decision criteria established during the first approach could be applied in the absence of a reference, thereby providing a configuration closely resembling in situ inspection conditions.

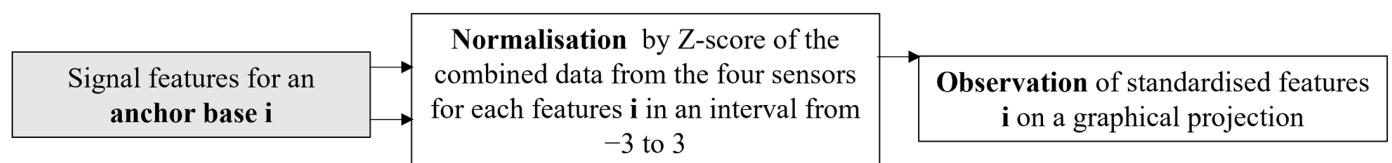


Figure 6. Z-score normalisation process applied to 4 sensors of an anchor base (i) by combining the data from all four sensors.

4. A.U. Results Obtained on Cables from Different Model Anchor Bases

4.1. Comparison of Anchor Cables Based on an Analysis of Power Spectral Density

The power spectral densities (PSDs) of the signals measured on the cables of the healthy reference and the different damaged anchor bases are presented in Figures 7 and 8. Although the PSDs were calculated for all sensors, only the results from two representative sensors are presented here: one positioned in a healthy area and the other in a damaged area of the cable from the same anchor base. The PSDs were obtained from the signals recorded by sensors 1 and 3 for each model anchor-base configuration in order to analyse the distribution of signal energy in the frequency domain.

Differences can be observed in the amplitude of the dominant PSD peak around 320 kHz, corresponding to the resonance frequency of the Micro80 sensor. The degraded cable exhibits a decrease in PSD amplitude of approximately 10 dB (13%) compared with the healthy reference state. This reduction reflects increased attenuation of the ultrasonic waves, probably due to scattering and energy dissipation phenomena induced by defects within the cable (Figure 7). The same reduction trend is also observed in the amplitude of the time-domain signals.

This behaviour can be attributed to changes in wave propagation within the damaged areas. Analyses carried out in both the time domain and the frequency domain revealed differences in amplitude between sensors located in the undamaged areas and those placed in the damaged zones. However, these analyses did not allow for a clear distinction to be made between the different levels of damage severity introduced into the model's anchor bases. The graphs in Figure 7 nevertheless show that the presence of a defect can be detected between the reference model base cable and the defective cables. In Figure 8, sensor 3 is located in an undamaged zone across all anchor bases; good consistency in spectral amplitude is observed for all the model's anchor bases, with the values remaining close to those of the reference anchor base shown in blue. A comparison of Figures 7 and 8

therefore highlights the difference between a sensor placed in an undamaged area and a sensor placed in a damaged area within the same anchor base.

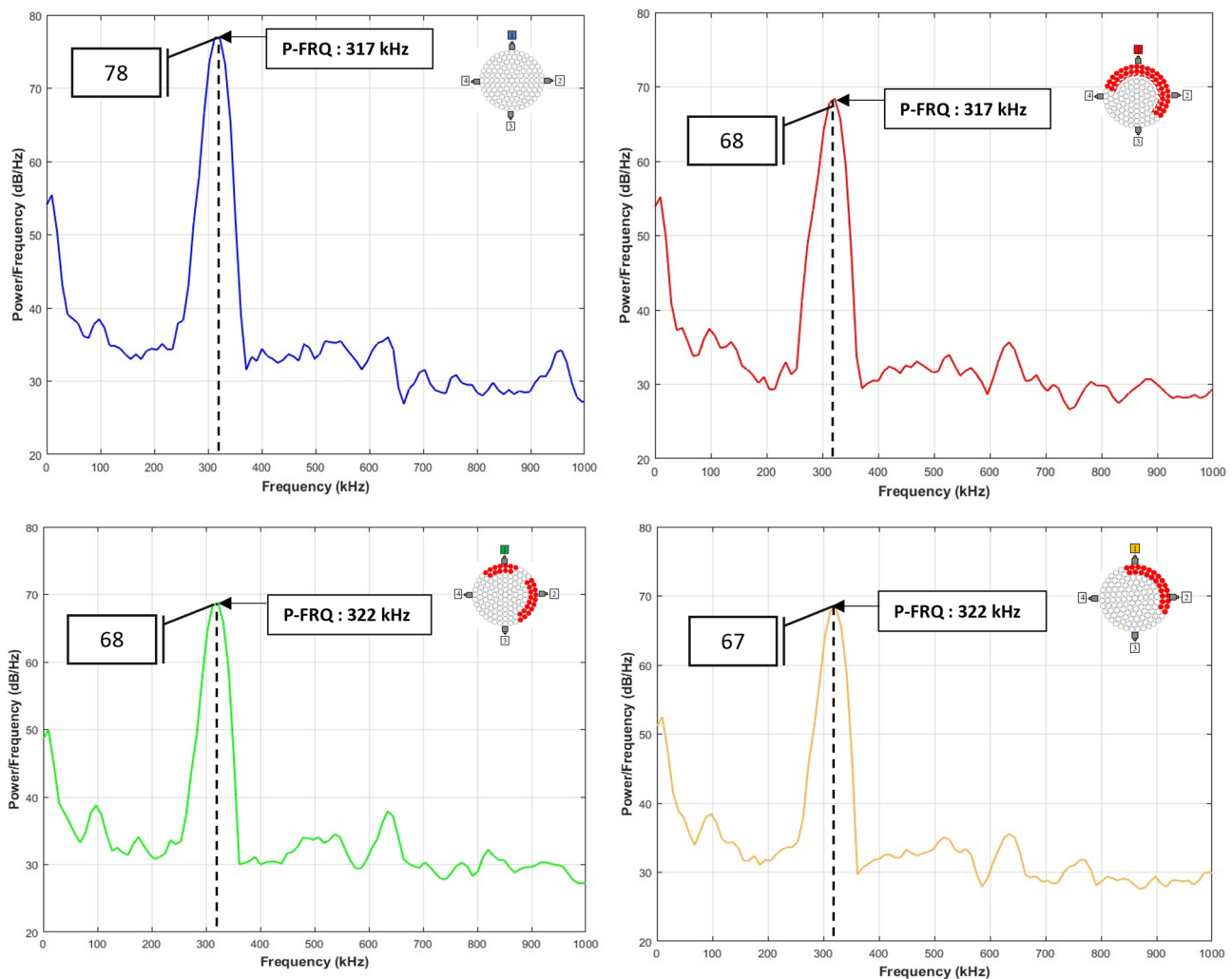


Figure 7. Power spectral densities (PSDs) of the signals measured by sensor 1 for the reference anchor base REF-1 (blue) and the three degraded anchor bases DEF-1Z, DEF-2Z AND DEF-W (red, green, and yellow).

Analyses in the time domain and frequency domain provide valuable information on the presence of damage in a cable depending on the location of the sensors, but they remain of limited use for rapid and reliable interpretation, particularly in the context of on-site inspections. PSD-based post-processing can nevertheless be a useful aid for more advanced decision-making. Consequently, the study then focused on descriptors extracted directly from the signals recorded by the Mistras system. This approach enables a simpler and faster analysis strategy to be proposed, offering greater potential for application under practical inspection conditions.

4.2. Defect Detection on the Cable with a Reference (AE Features)

The comparison of cable behaviour was carried out between two anchor bases: a healthy reference base (REF-1) and the damaged anchor bases (DEF-1Z, DEF-2Z et DEF-W). The acoustic emission (AE) features listed in Table 2 were analysed using the normalisation procedure. After normalisation of the data, it is then relevant to examine the results obtained from all sensors positioned around the cable. To this end, the feature data from the healthy reference base (REF-1) are compared with those from the degraded base (DEF-1Z).

Figures 9–11 present the normalised data: values associated with the reference base are shown in blue, while those corresponding to the DEF-1Z base are shown in red, the features presented are centroid frequency (C-FRQ), amplitude (AMP), and counts to peak (PCNTS). Sensors 1 and 2 are aligned with the broken wires inside the anchor base, whereas sensors 3 and 4 are aligned with regions of the cable considered healthy. For sensors 1 and 2, the distributions associated with the damaged anchor base display a clear deviation from the reference data, with values generally shifted towards positive normalised values. These deviations reflect changes in signal characteristics, likely resulting from the interaction of ultrasonic waves with structural discontinuities caused by broken wires.

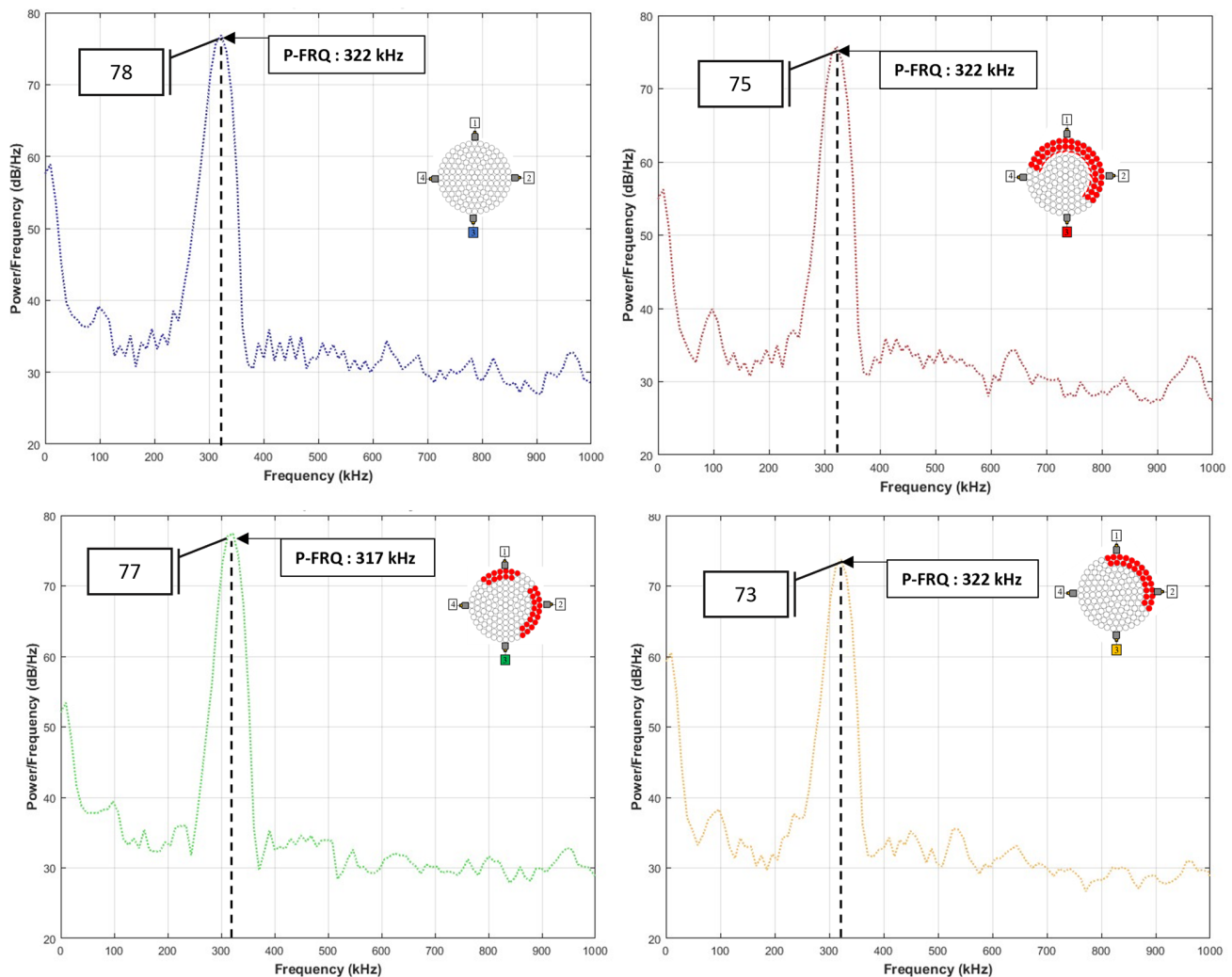


Figure 8. Power spectral densities (PSDs) of the signals measured by sensor 3 for the reference anchor base REF-1 (blue) and the three degraded anchor bases DEF-1Z, DEF-2Z AND DEF-W (red, green, and yellow).

Conversely, for sensors 3 and 4, the distributions associated with the degraded base remain closer to those of the healthy reference. In some cases, the distributions partially or even completely overlap, suggesting that the influence of defects decreases significantly with distance from the damaged area. This behaviour corresponds well to the localised nature of produced damage (see Table 1) and its local influence on wave propagation.

Figure 11 shows the results obtained for the normalised descriptor PCNTS. In this case, the distributions do not show clear consistency with the sensor positions, and the data obtained are highly heterogeneous. This indicates that this feature is less effective at distinguishing damaged areas under the experimental conditions considered.

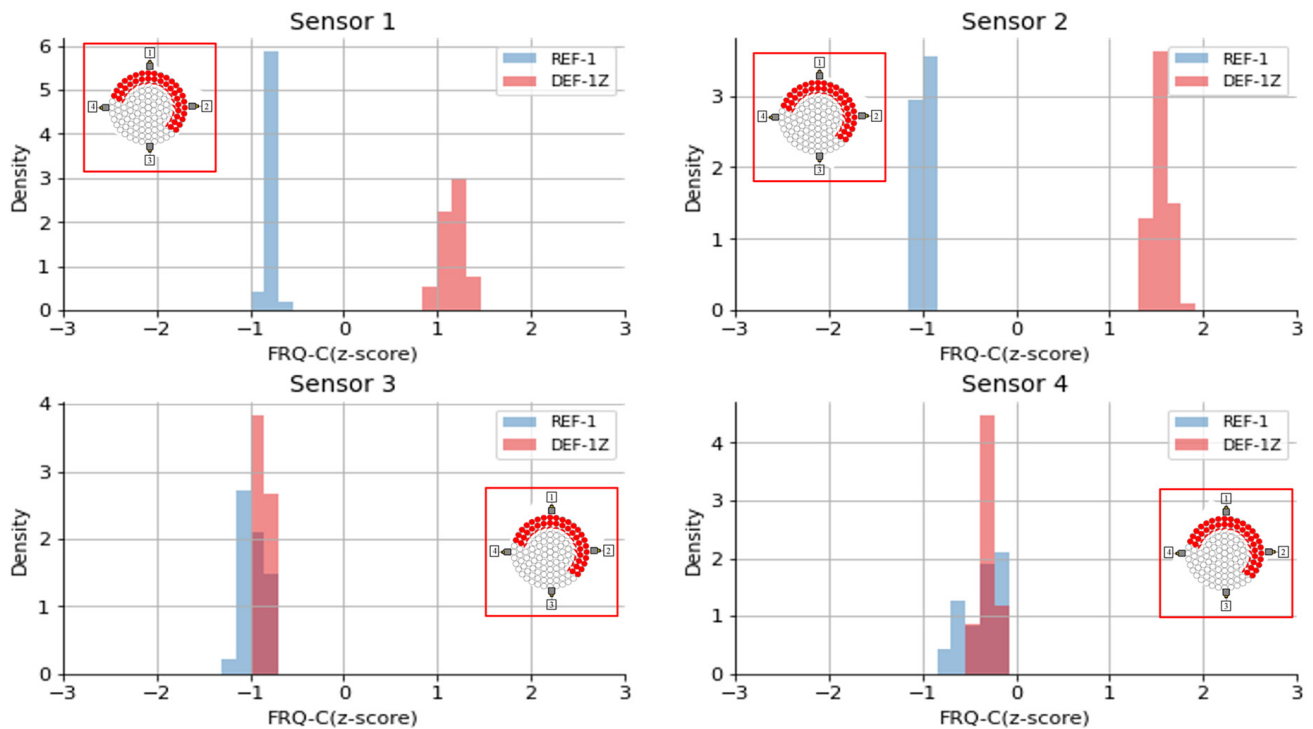


Figure 9. Distributions of normalised Freq-C feature for a healthy reference cable (REF-1) and for a damaged one (DEF-1Z).

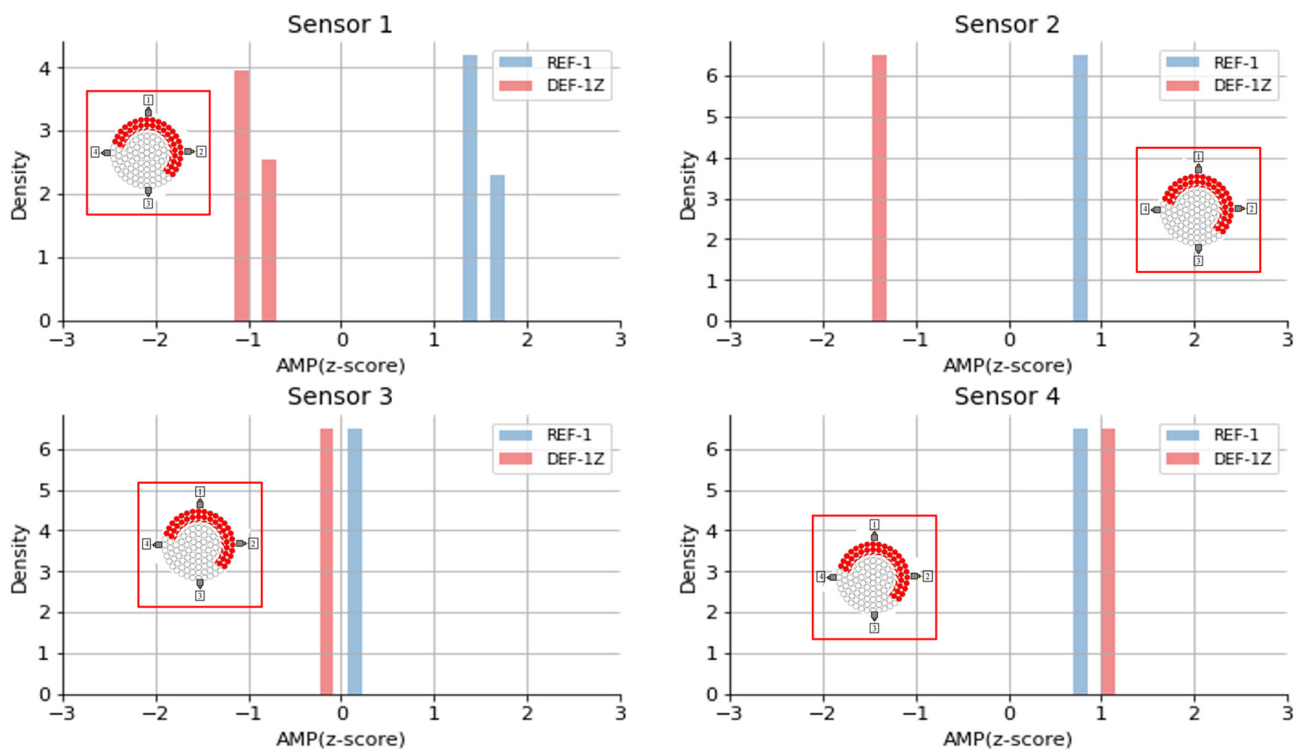


Figure 10. Distributions of normalised amplitude feature for a healthy reference cable (REF-1) and for a damaged one (DEF-1Z).

In Figures 9 and 10, the normalised data obtained from the various sensors show a consistent trend within each group of sensors. These variations appear to be in relation with the positions of the sensors on the cable, whether they are located opposite a healthy section or a damaged section.

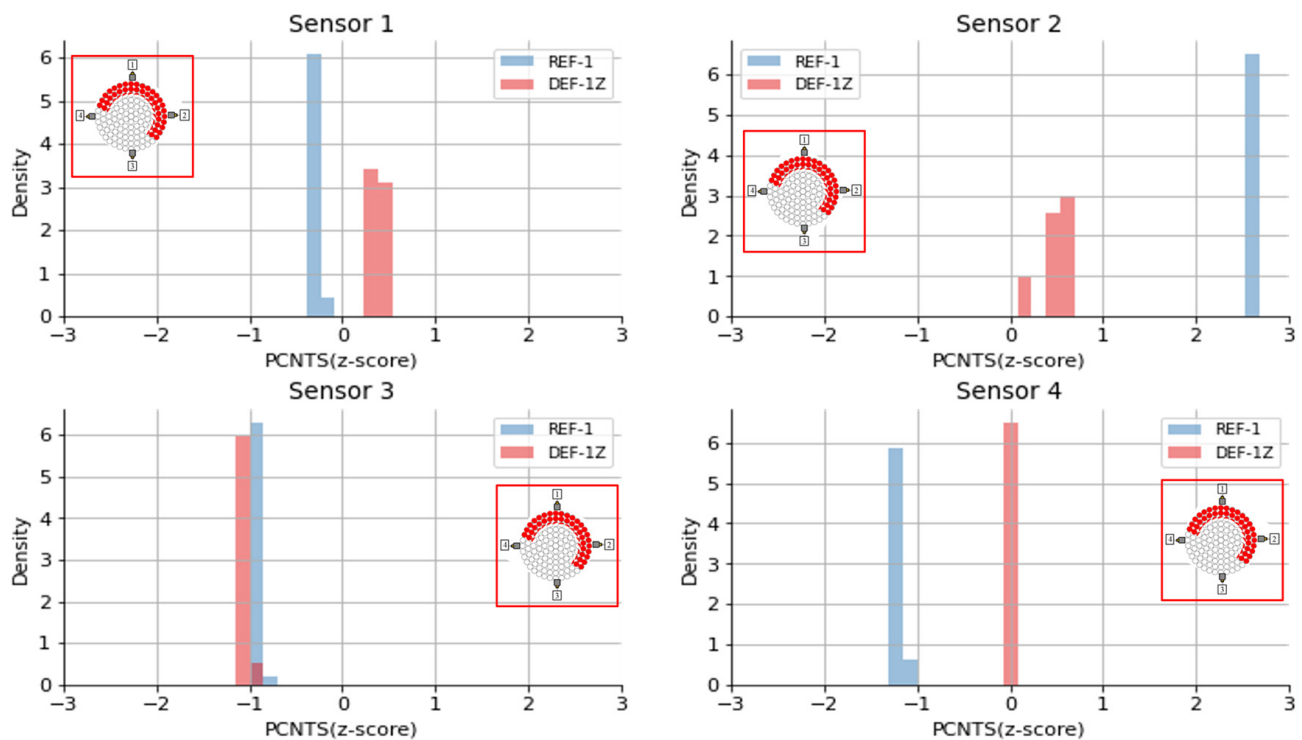


Figure 11. Distributions of normalised counts to peak (PCNTS) feature for a healthy reference cable (REF-1) and for a damaged one (DEF-1Z).

The relevance of each feature was assessed using a selection criterion. The latter is based on the difference between the sensor responses obtained on the reference anchor base and those measured on the anchor bases with defects. A feature is considered relevant when the difference between the values normalised using the Z-score method is greater than 1.5 between a sensor on a healthy area and a sensor on a damaged area, and when its variations are consistent with the expected condition of the cable. The threshold value of 1.5 was determined on the basis of ten repeated inspections of the reference anchor base, for which the maximum difference between the normalised responses of the four sensors did not exceed 1.5 for the selected characteristics.

The selection criteria were then tested using data from several tests carried out on all anchor bases. For each case, three tests were carried out, and each dataset was normalised in conjunction with that of the reference anchor base (Figure 5) for establish a set of relevant features to assess the condition of the cables. The repeatability of the trends suggests that the differences identified between the reference and the degraded states are not due to variations in coupling conditions, but are more closely related to the presence of damage in the cable.

This analysis thus enabled the selection of the acoustic emission features for the subsequent tests carried out on the anchor bases, namely amplitude, energy, counts, centroid frequency, signal strength, and absolute energy.

The features selected previously were then evaluated using a decision criterion in order to analyse their reliability across all degraded anchor bases condition. This criterion is based on the sign of the normalised values. For features in the time domain, a positive normalised value is associated with a healthy condition, whilst a negative value is associated with a damaged condition. For features in the frequency domain, this trend is reversed; the interpretation therefore relies on the consistency between the sign of the normalised values and the expected condition of the cable, depending on the positioning of the sensors.

For each degraded anchor base condition, three comparisons with the reference base were carried out. The results are presented in Table 3. Each feature was evaluated for each defect configuration, considering the four sensors and the three tests carried out. Applying the decision criterion defined above thus enabled a score to be assigned to each feature in order to estimate its ability to distinguish between healthy and degraded cable areas.

Table 3. Score obtained after three measurements, taken using the eight sensors for each feature, by comparing the REF-1 with the degraded anchor bases (DEF-1Z, DEF-2Z and DEF-W), applying the decision criterion based on the sign of the normalised data (positive or negative).

Features Tested on 3 Tests	Score Obtained on the DEF-1Z Base	Score Obtained on the DEF-2Z Base	Score Obtained on the DEF-W Base	Total Score for All Degraded Bases
Amplitude	12/12	11/12	10/12	33/36
Counts	7/12	8/12	12/12	27/36
Centroid Frequency	11/12	9/12	8/12	28/36
Energy	7/12	9/12	11/12	27/36
Signal Strength	7/12	9/12	11/12	27/36
Absolute energy	9/12	8/12	7/12	24/36
Total score for the features of an anchor base	53/72	54/72	59/72	

The results show that the most effective feature is amplitude, with a score of 33/36 across all degraded anchor base conditions. The performance of the other features remains relatively close, however, confirming their value for assessing the condition of cables within their anchor bases. Furthermore, the scores obtained for the various anchor bases are globally similar, whatever the type of damage considered. This suggests that the geometry of the damage introduced into the anchor bases has no clearly observable influence on the ability of the features to detect the presence of defects.

Thereafter, the model anchor bases will be analysed without normalisation relative to the reference base. This approach aims to replicate the actual on-site monitoring conditions as closely as possible, where the reference condition is not available. It will also enable the robustness of the decision criterion established previously.

4.3. Defect Detection on the Cable Without Reference (AE Features)

After comparing a reference cable and a degraded cable in their model anchor bases, and after defining criteria to distinguish between healthy and degraded states, the analysis of cables without reference nevertheless appears to be a major challenge during in situ inspections, since no reference state is then available for comparison. In this context, all descriptors were first tested. Subsequently, the graphs presented in this article focus on two descriptors, amplitude (AMP) and energy (ENER), considering all sensors. The data from both configurations were normalised and the decision criteria previously defined for these features applied. The normalised amplitude and energy for each anchor base are presented in Figures 12 and 13. Sensors 1 and 2 are positioned along the extension of the broken wires for both anchor bases, while sensors 3 and 4 are located in areas considered to be healthy. The DEF-W and DEF-2Z configurations show a good agreement between the data and the sensor positioning: negative values are predominantly observed for sensors 1 and 2, whereas sensors 3 and 4 exhibit positive values (with the exception of sensor 3 for DEF-W in terms of energy). Overall, the results demonstrate a good consistency with the previously defined criteria.

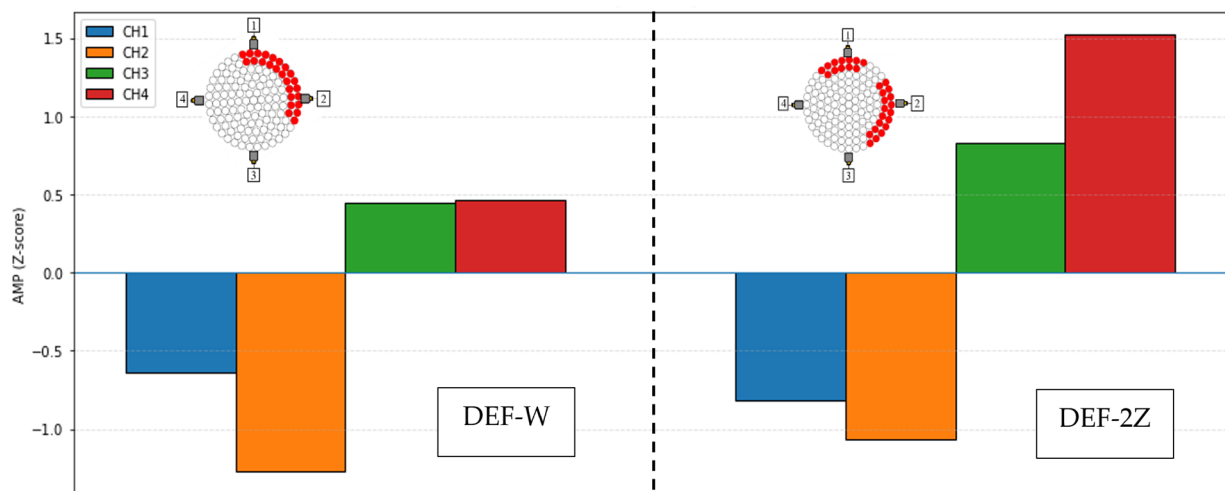


Figure 12. Normalised amplitude across all sensors for the DEF-W and DEF-2Z anchor bases (reference-free analysis).

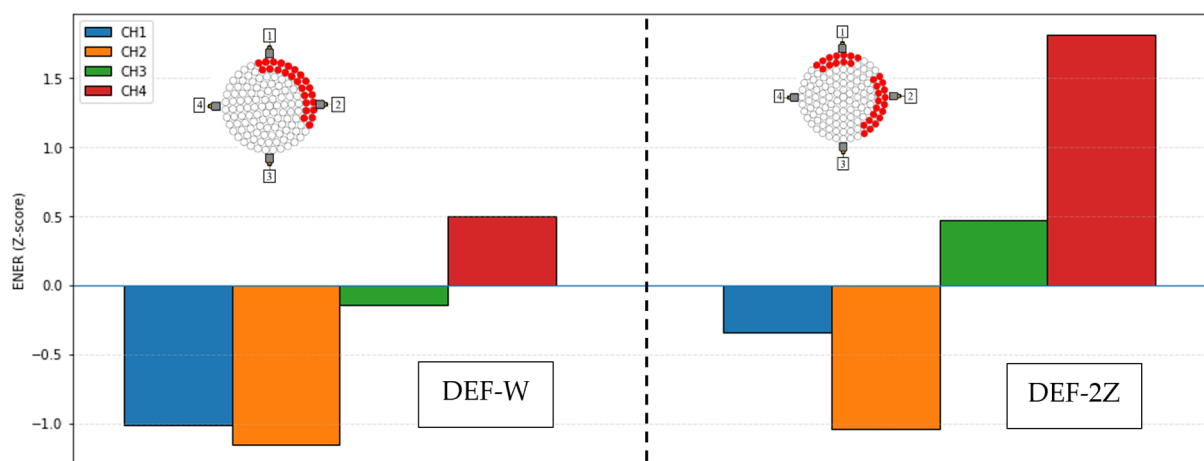


Figure 13. Normalised energy across all sensors for DEF-W and DEF-2Z anchor bases (reference-free analysis).

In order to evaluate the criterion defined in the previous section, further tests were carried out to determine the error rate of the selected features. To this end, five tests were carried out on each of the degraded anchor bases. The error rates obtained for all configurations are presented in Table 4. The results show that the error rates associated with the selected features remain generally below 20%. Among these, amplitude appears to be the most relevant feature, with an average error rate of 11.7% across all the anchor bases studied. It is also observed that the geometry and damage configuration of the anchor bases influence detection performance. The best results are obtained for the DEF-1Z and DEF-2Z anchor bases, for which the distinction between sound and degraded areas is clearer. These results confirm the relevance of this criterion for cable monitoring in model anchor bases without the use of a reference anchor base.

It is also useful to accurately locate the damaged section of the cable; to do this, we examined which sensors exhibit classification errors and in which areas (healthy/degraded) these errors occur. This analysis is presented in Table 5. Across all the selected features, the acoustic-ultrasonic method enables the correct identification of sensor positions relative to healthy and degraded areas. Error rates remain low for the DEF-1Z and DEF-2Z bases, indicating a good ability to distinguish between sensors located near damaged areas and those positioned on areas considered healthy. In contrast, a higher error rate is observed

for the DEF-W base. This result suggests that the geometry of the defect can influence the response measured by the sensors. However, despite these variations, each degradation configuration remains detectable using the selected features. These results also show that the AU method offers the possibility of locating the defect zone on the cable, considering the relative position of the sensors around the inspected area.

Table 4. Determination of error rates obtained for the selected descriptors by applying the discriminant criterion based on the sign of the values normalised to 0. The results are calculated from five inspections carried out on each degraded anchor base in order to assess the performance of each descriptor in relation to the damage to the cable.

Features	DEF-1Z	DEF-2Z	DEF-W	Total Score for All Degraded Bases
Amplitude	10%	5%	20%	11.7%
Counts	15%	25%	15%	18.3%
Centroid Frequency	5%	20%	30%	18.3%
Energy	15%	10%	20%	15%
Signal Strength	15%	15%	20%	16.7%
Absolute energy	15%	15%	25%	18.3%
Total	12.5%	15%	21.7%	

Table 5. Determination of the error rate in the sensor's identification of whether an area is sound or degraded. The results are calculated on the basis of the five scans carried out for each anchor base by combining the selected descriptors.

Inspected Area	DEF-1Z	DEF-2Z	DEF-W
Error rate for sensors positioned in healthy cable areas	16.7%	25%	31.7%
Error rate for sensors positioned in damaged cable areas	13.3%	18.3%	25%

Under in situ conditions, the location of the damage in the cable within its anchor base is not known in advance. The protocol must therefore be adapted so that it does not depend on a known degraded area or a reference point. The analysis must then be based primarily on a comparison of the responses from the various sensors placed around the cable. The criterion defined previously must be used as a decision-making aid to detect and locate a degraded area.

4.4. Validation of the In Situ Protocol on Anchor Model

The protocol adopted for on-site inspections involves taking two successive measurements. During the first measurement, the sensors are positioned around the cable at 90° intervals. The sensors are then rotated by 45° before the second measurement, thereby inspecting the entire circumference of the cable; the number of measurements may vary depending on the cable's diameter. The transmission sensor is kept in the same position during both inspections to maintain identical transmission conditions. This protocol was evaluated on the DEF-W anchor base, which had the highest error rate, considering two configurations for positioning the receiving sensors, as illustrated in Figure 14. This configuration allows the acousto-ultrasonic method to be tested for its ability to detect a degraded area when the exact position of the defect is not known in advance, which more closely corresponds to actual on-site inspection conditions.

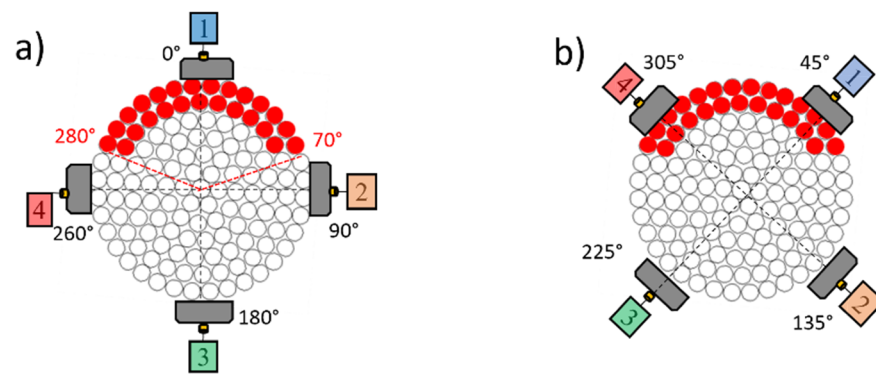


Figure 14. (a) First arrangement of the receiving sensors around the cable, with sensor 1 positioned in a degraded area, along with the angular markers for that area; (b) second arrangement of the receiving sensors around the cable, with sensors 1 and 4 positioned in a degraded area.

The results obtained, illustrated in Figure 15, demonstrate consistency between the two tests regarding the positioning of the sensors in relation to the degraded area. During the first test, sensor 1 exhibited a negative value. After angle rotation, sensors 1 and 4 showed values below 0. These observations indicate that the defined criterion remains applicable within the framework of the protocol established for the in situ inspection of the cables in their anchors. They also show that the defect can be located by cross-referencing the data from the two successive inspections.

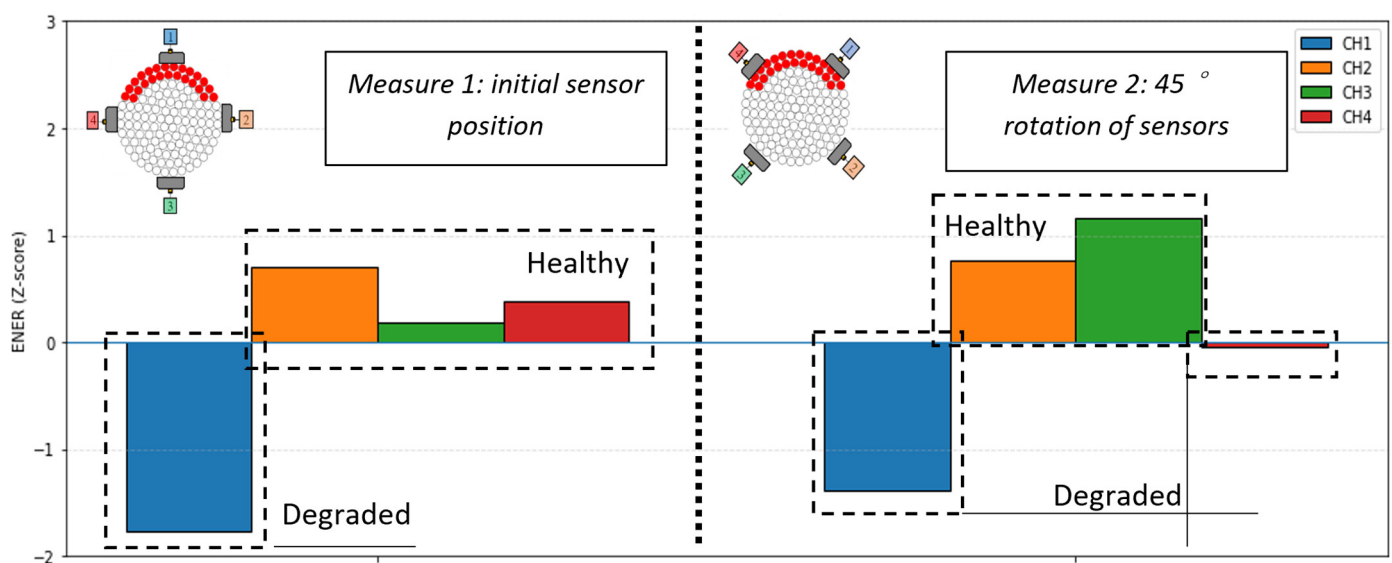


Figure 15. Normalised energy results obtained during the two measurement campaigns for the DEF-W anchor base.

5. Conclusions

This study highlights the potential of the acoustic-ultrasonic (AU) technique, combined with an analysis based on acoustic emission features, for assessing the condition of cables within their anchor bases. Initially, signal analysis was carried out using power spectral density, estimated by the Welch method, in order to observe differences in response between sensors depending on their positioning around the cable. This initial approach revealed variations in the frequency content and energy level of the signals between healthy and degraded configurations. In particular, a decrease of approximately 13% in the dominant PSD peak around 320 kHz was observed in the damaged cable regions compared with the healthy reference. However, with a view to in situ application, the study then focused

primarily on the analysis of features extracted from the signals, which are more readily usable for rapid decision-making.

The first step was a comparison of the responses obtained from a reference anchor base with those measured on the degraded model bases condition. This comparison, combined with Z-score normalisation, made it possible to identify the most relevant descriptors for inspecting cables within their anchors. Based on these descriptors, an evaluation criterion was defined to discriminate healthy or degraded zones from the sensor locations around the cable. Amplitude provided the lowest average error rate, remaining below 12%, whereas the other selected features (counts, centroid frequency, energy, signal strength and absolute energy) showed average error rates above 12%.

This criterion was then applied to model anchor bases with broken wires without using the reference anchor base, in order to more closely replicate on-site monitoring conditions, where a reference condition is generally not available. The results obtained made it possible to assess the error rates associated with different defect geometries and to analyse the response of the sensors according to their position around the cable. The most discriminating features showed consistent results, confirming their value for detecting cable damage in anchor bases. These results also illustrate that the proposed method can not only be an aid in the detection of damage, but also provides indications of its probable location around the cable.

Finally, the last part of the study focused on evaluating an inspection protocol adapted to in situ conditions, applied to a degraded cable condition. This protocol is based on two successive tests/inspections with an angular displacement of the receiving sensors. This approach represents an important step towards the transfer of the acoustic–ultrasonic method to practical inspections of structures.

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