engineering proceedings

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Proceeding Paper

Method for Damage Detection of CFRP Plates using Lamb Waves and Digital Signal Processing Techniques

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Abstract: The identification and severity of structural damages in carbon fiber reinforced polymer (CFRP), especially in the early stage, is critical in structural health monitoring (SHM) of composite materials. Among several approaches used to accomplish this goal, ultrasound inspection using Lamb waves has taken place within non-destructive testing (NDT) methods. Likewise, the use of digital signal processing techniques for structural damage diagnosis has become popular due to the fact that it provides relevant information through feature extraction. In this context, this paper presents an alternative strategy based on the use of RMSD and CCDM representative indices to extract the most sensitive information related to damage in CFRP plates through ultrasonic NDT signals in specific frequency ranges. In the experimental analysis, CFRP coupons were subjected to two types of damages: cracking and delamination. The signals, generated by piezoelectric transducers attached to the host structure using the pitch-catch method of Lamb waves, were subject to signal processing parameters based on the proposed approach. The results reveal that the proposed method was able to characterize the different types of damage in CFRP, as well as their severity in specific frequency bands. The results indicate the feasibility of the proposed method to detect and characterize damage in composite materials in a simple way, which is attractive for industrial applications.

Keywords: CFRP; SHM; damage detection; signal processing; Lamb Waves; piezoelectric transducers

Citation: Monson, P.; Junior, P.O.C.; Rodrigues, A.R.; Aguiar, P. Method for Damage Detection of CFRP Plates using Lamb Waves and Digital Signal Processing Techniques. *Eng. Proc.* **2022**, *4*, x. https://doi.org/10.3390/xxxxx

Academic Editor: Stefano Mariani

Published: 1 November 2022

1. Introduction

The adoption of composite materials, such as carbon fiber reinforced polymer (CFRP) has been increasing in the last decades, being extensively employed in structural components in several areas, due to its physical and mechanical characteristics, such as high strength, stiffness, weight, and corrosion resistance [1–3]. It must be emphasized that CFRP has been gradually replacing traditional metallic alloys in the development of the aeronautical industry recently, providing performance improvements, thanks to the weight reduction that, in some cases can reach up to 50% of the total weight of the aircraft [4,5]. However, the use of CFRP presents some challenges when applying it in engineering projects, due to the anisotropic nature of composite materials and the incidence of well-known damages, such as fissures and delamination. Fissures, usually a precursor to delamination, occur in the matrix and perpendicular to the fiber direction, causing an interlayer stress concentration. The development of this damage causes delamination, through the concentration of stress between the layers, which reduces their resistance and, in some cases, can lead to total failure of the structure [3]. The increased use of CFRP, motivates the development of novel methods for monitoring these structure's integrity, to detect the damage progression, providing actions to mitigate the possible identified failures, thus ensuring the required safety levels for this material usage [6]. In this scope, the structural health monitoring (SHM) of this material is presented as a viable solution to address this problem. SHM is the subject of several research, and there is a wide range of tools and techniques to evaluate the material's condition during its life cycle. A technique known as non-destructive testing (NDT) is a method that interrogates the structure with transducers at various stages of its life cycle, causing no damage to the structure during its use, and being able to provide information about possible failures to the monitored equipment. One technique of this kind of test uses guided waves to emit a signal that travels through the structure under analysis, this signal is received by a sensor and used to extract characteristics that can provide information about its current condition [7,8]. Currently, there is a wide range of sensors that can be used in SHM applications, being possible to emphasize the piezoelectric transducers, widely used because of their low cost and easy implementation, these sensors can also be used as actuators due to the piezoelectric effect [7], [8]. Similarly, several signal processing techniques and data-driven approaches using machine learning has been reported for damage detection in CFRP, where condition indicators based on the change in power spectral density, energy, and time of flight [9], as well as Gaussian discriminant analysis [10], and damage index based on fissure density in the polymer matrix [1], have been used to characterize and classify sample damage.

In this work, an alternative approach for damage detection in CFPR structures is proposed, based on piezoelectric transducers and the Lamb wave method in association with digital signal processing techniques. The method was evaluated through application in experimental CFRP structures in order to detect two types of failures, cracking and delamination, in comparison to the baseline. The main contribution of the present study is the application of RMSD and CCDM metrics to evaluate the damage incidence from a specific frequency band and for different types of composite failures, which have not been reported in the literature related to this dataset yet. This work aims to advance knowledge regarding damage detection methods in composite materials and to present a simple and low-cost solution for industrial applications.

2. Materials and Methods

The dataset used in this study was obtained from an experimental fatigue test on CFRP composites, conducted by the Stanford Structures and Composites Laboratory (SACL) in cooperation with the Prognostic Center of Excellence (PCoE) at the NASA Ames Research Center [9]. This public dataset has been used by many authors, such as [1,3,10–13].

The composite samples were prepared using a 254 × 152.4 mm Torayca T700G unidirectional prepreg composite. The samples have a dogbone geometry and a 19.3 × 5.08 mm notch, as illustrated in Figure 1, to provide stress concentration.

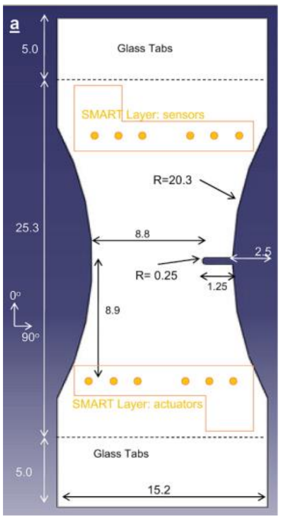


Figure 1. CFRP coupon prepared for fatigue testing [10].

For monitoring the fatigue test damage, two sets were used, with six SMART Layer® piezoelectric zirconate titanate (PZT) transducers each, developed by Acellent Technologies Inc., arranged in a pitch-catch configuration. This configuration allows monitoring the Lamb wave propagation in 36 different trajectories.

The samples prepared with sensors and actuators were subjected to cyclic loading. At the test beginning, the transducer signals are collected in order to determine the initial condition of the structure. At the end of a sequence of cycles, the structure is evaluated again, the signals are collected, and the sample is submitted to an X-ray examination to verify the occurrence of damage. Then, a count of the visual cracks is done, and the values are inserted into an electronic spreadsheet that follows the data set. Information about delamination behavior is also reported.

For this study, it was used the data from the sample labeled by the experiment authors as L1S11, belonging to Layup 1 with the layer configuration $[0_2/90_4]_S$.

2.1. *Proposed Methodology*

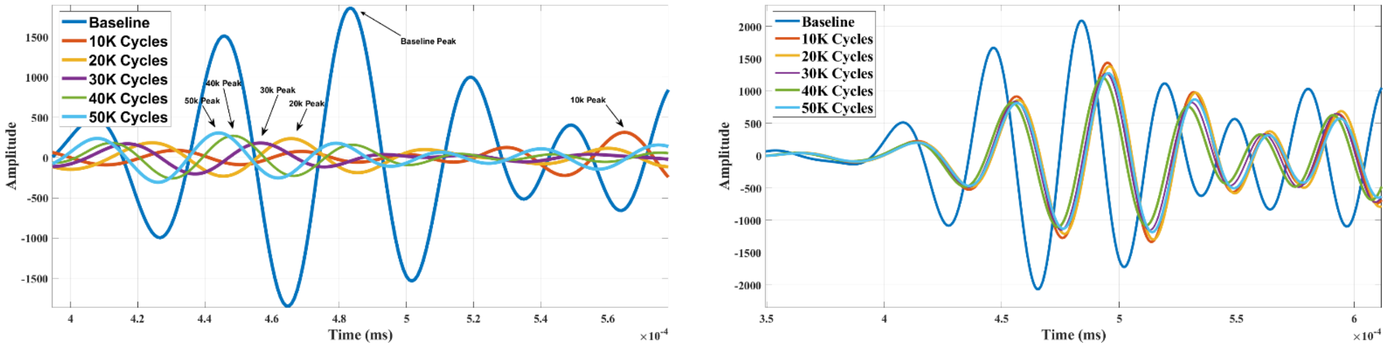
In this study, is performed an analysis of the data set described before, in order to evaluate the behavior of the signals acquired from the piezoelectric transducers as CFRP sample degrades. For this, it was used trajectory 5–8, chosen for the presence of delamination as the CFRP coupon is subjected to the fatigue process, and trajectory 3–10, to evaluate microcracking. This analysis was performed in the time domain, evaluating the amplitude and displacement patterns of the signal according to the structural damage. The frequency spectrum analysis of the signals was performed using the fast Fourier transform (FFT), calculated with a Hanning windowing, to identify the most sensitive frequency bands to the damage. Widely used damage indices in SHM such as the root mean square deviation (RMSD) and correlation coefficient deviation metric (CCDM) were also applied, following the approach published by [14] comparing the initial condition signal with the observed damage signals in the x-ray examination of the sample.

3. Results and Discussion

As mentioned previously, the selected trajectories were 5–8 and 3–10. The analyses of each selected trajectory were performed using the signals collected between 100 and 60 thousand cycles of the experimental test. This range comprises the most significant damage progression suffered by the sample. The results of the time and frequency domain analyses, as well as the damage indices, are presented below.

3.1. Time-Domain Analysis

Initially, a time domain analysis was performed for the signal acquired by the transducer illustrated in Figure 2, in which it is possible to observe the behavior patterns for the different classes of damage present in the sample. Figure 2a shows the signal pattern with delamination in the structure, where it is possible to observe a reduction in signal amplitude compared to the baseline condition, and also the displacement of the signal peaks, caused by the damage progression in the sample. The signals from trajectory 3–10, shown in Figure 2b, where the only damage is due to the micro-cracking, have more regular comportment, with the signal amplitude attenuation and displacement to the opposite direction presented in the trajectory with delamination.

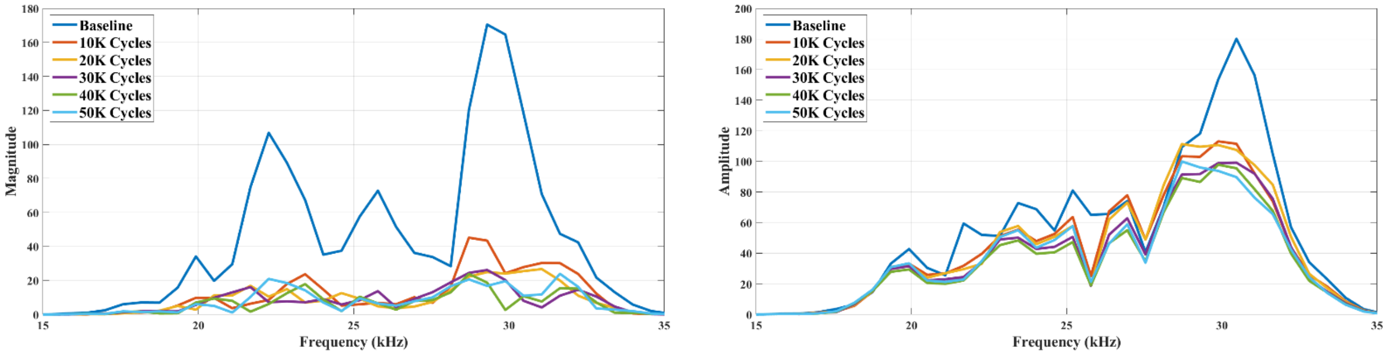


(**a**) (**b**)

Figure 2. Time-domain signals for (**a**) 5–10 and (**b**) 3–8 path.

3.2. Frequency-Domain Analysis

By using the Fast Fourier Transform (FFT), the frequency spectrum was analyzed. Figure 3 shows the spectral behavior of the trajectory with delamination (Figure 3a), where it is evident a significant reduction of the magnitude as the delamination progresses, as well as the main bands where the damage happens. As observed previously, path 3–10 (Figure 3b) presents a magnitude reduction characteristic, not as pronounced as the one caused by delamination, as fissures occur in its matrix. With this analysis, in the next step, damage metrics will be calculated to identify the frequency bands most susceptible to damage.

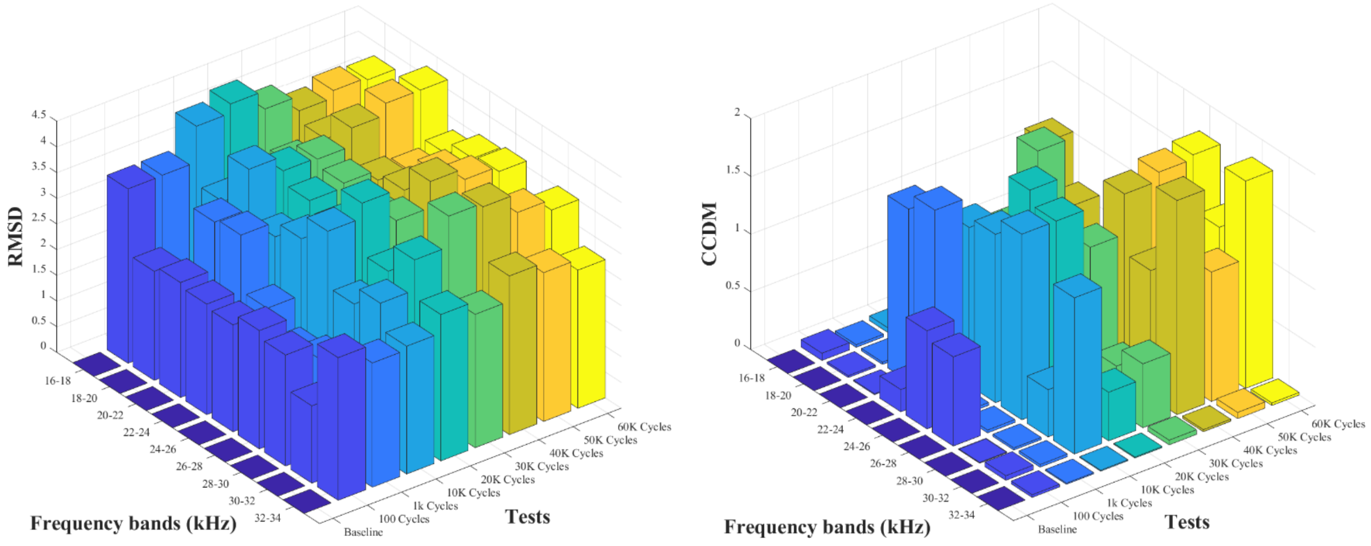


(**a**) (**b**)

Figure 3. Frequency-domain signal for (**a**) 5–10 and (**b**) 3–8 path.

3.3. Damage Indices

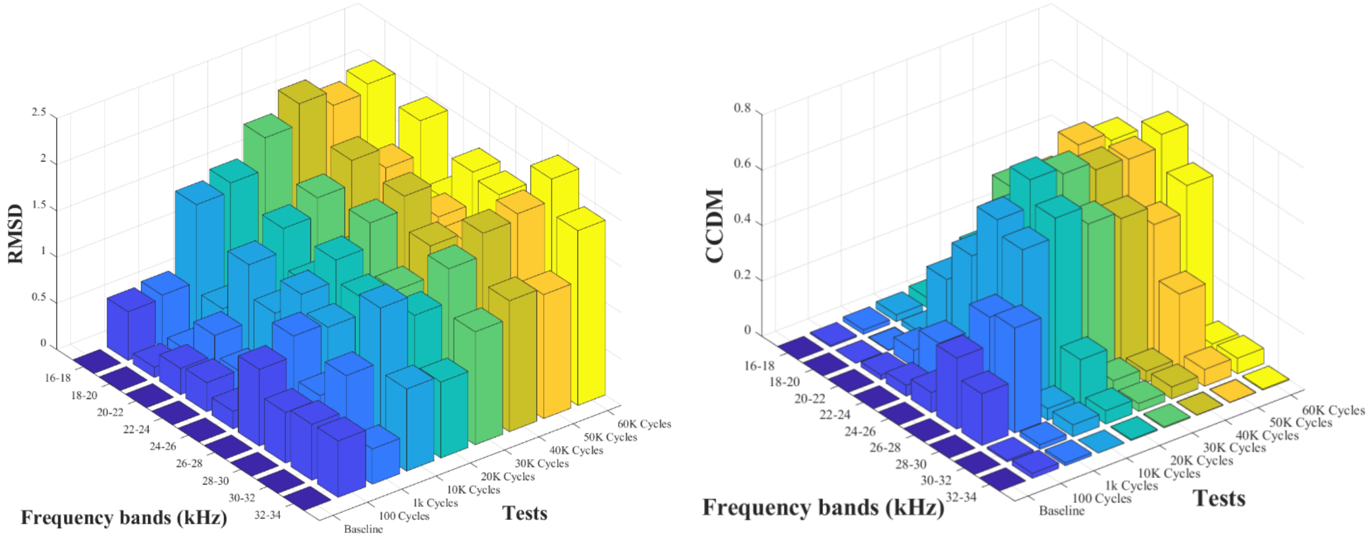
To contribute to the analysis of the damage present in this data set, the RMSD and CCDM indexes were calculated for the two damage classifications. These indices allow the comparison of signals obtained with samples in pristine conditions (baseline), with the signals that may present some kind of damage. For both types of damage were adopted a 16 to 34 kHz band, with a 2 kHz range, using the FFT magnitude values. Figure 4 shows the RMSD (Figure 4a) and CCDM (Figure 4b) calculated with the delamination signal. The results indicate that frequency bands from 20 to 22 kHz (RMSD) and 28 to 30 kHz (CCDM) are more sensitive for the characterization of the delamination severity suffered by the coupon.



(**a**) (**b**)

Figure 4. Damage indexes (**a**) RMSD and (**b**) CCDM index for 5–8 path with delamination.

Using the same parameters, the indices were calculated for the trajectory with fissures. Figure 5 presents the RMSD (Figure 5a) and CCDM (Figure 5b) indices calculated for the delamination signal. This analysis evidences the capacity of these metrics in detecting the fissure progression in several stages of the sample's lifetime, particularly in the bands from 30 to 32 kHz for the RMSD metric and 24 to 26 kHz for the CCDM metric, being a useful solution when applied in industrial engineering projects. The solution is also notable for its simplicity and low computational cost since the most representative frequency bands for damage are below 40 kHz.



(**a**) (**b**)

Figure 5. Damage indexes (**a**) RMSD and (**b**) CCDM index for 3–10 path with microcracks.

4. Conclusions

In this work, a study was conducted regarding the use of signal processing techniques to develop a methodology for classifying damage levels in CFRP structures using the Lamb wave method. Where the signals presented in the dataset were subjected to analysis in the time and frequency domain, and also applying damage metrics used in SHM applications to provide characteristics about the damage in these samples.

The analysis demonstrated that is possible, through the applied tools, to extract characteristics able to correlate the signal obtained by the sensors with the damages observed in the structure as well as their severity, as evidenced by the application of the RMSD and CCDM metrics. The proposed methodology shows to be viable for industrial applications, characterized by using low-cost transducers and reduced computational processing, allowing the implementation of the method in a low-end hardware.

Author Contributions Conceptualization, P.M.C.M. and P.O.C.J.; methodology, P.O.C.J.; software, P.M.C.M. and P.O.C.J.; validation A.R.R., P.O.C.J., P.A. and C.S.J.; formal analysis, P.M.C.M. and P.O.C.J.; investigation, P.O.C.J. and A.R.R.; writing—original draft preparation, P.M.C.M. and P.O.C.J.; writing—review and editing, P.O.C.J., A.R.R. and C.S.J.; visualization, X.X.; supervision, P.O.C.J. and A.R.; project administration, P.O.C.J. All authors have read and agreed to the published version of the manuscript.

Funding:

Institutional Review Board Statement: Not applicable.

Informed Consent Statement:

Data Availability Statement: Not applicable.

Acknowledgments: This study was financed in part by the Coordenação de Aperfeiçoamento de Pessoal de Nível Superior—Brasil (CAPES)—Finance Code 001.

Conflicts of Interest: The authors declare no conflict of interest.

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