ROBUST PARAMETRIZATION FOR NON-DESTRUCTIVE EVALUATION OF COMPOSITES USING ULTRASONIC SIGNALS

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ABSTRACT
Anticipating and characterizing damages in layered carbon fiber-reinforced polymers is a challenging problem. Non-destructive evaluation using ultrasonic signals is a well-established method to obtain physically relevant parameters to characterize damages in isotropic homogeneous materials. However, ultrasonic signals obtained from composites require special care in signal interpretation due to their structural complexity. In this paper, some enhancements on the interpretation are done by adapting classical parametrization techniques to extract relevant features from the ultrasonic signals. Thus, a cepstral-based feature extractor is firstly designed and optimized by using a classification system based on cepstral distances. Then, this feature extractor is applied in an analysis-by-synthesis scheme which, by using a numerical model of the specimen, infers the values of the damage parameters.

Index Terms— Signal processing, feature extraction, non-destructive evaluation, ultrasonics

1. INTRODUCTION
Non-destructive evaluation (NDE) is an emerging technology that enables to raise the remaining life and reliability of nowadays structures, as well as to characterize advanced materials or biomaterials in medical science. Quantitative non-destructive evaluation (QNDE) techniques are based on the use of theoretical models of wave propagation to extract additional information from experimental measurements [1].

An essential element in NDE systems is the analysis of the captured signal, to obtain relevant information from the tested specimen. First works on feature extraction mainly focused on filtering techniques: Rodriguez et al. [2] selected the frequency range corresponding to the detected echoes location, while Bilgutay et al. [3] proposed a transformation based on filter-bank techniques by applying the split spectrum processing (SSP) method to obtain a reconstructed signal less affected by noise. Later proposals aboard the deconvolution problem in NDE by applying classical techniques, such as the Wiener filter and the spectral extrapolation [4], or homomorphic deconvolution by computation of the cepstrum [5]. In particular, the cepstrum has been used as an efficient parametrization tool for ultrasonics signals, since the cepstral coefficients involve deconvolutionated signal information [6]. In some cases, the extracted signal parameters can be processed again to reduce the dimensionality of the feature vectors, by applying classical linear discriminant analysis (LDA) [7], or principal components analysis (PCA) [8].

However, most of the above-mentioned applications deal with a simple determination of the presence of damages in the evaluated specimen. Thus, the final step of the system is limited to a classification between damage/no-damage states, requiring a huge amount of experimental data and an expensive training process, without providing any information at the physical level.

This study focuses on the application of the cepstrum LPC to discriminate the damage level of a carbon-fiber reinforced polymer (CFRP) plate subjected to several impact energies. First, the discriminative capability of this cepstrum is evaluated using a system that classifies the damage level corresponding to a test signal. Finally, the most effective encountered parametrization is inserted in a structure of analysis-by-synthesis, which compares the numerically predicted signals obtained from a physical model of propagation with the experimental ones measured from the specimen. In such a way, by means of an optimization procedure, physically relevant damage parameters are obtained.

The rest of this paper is organized as follows: Section 2 exposes the NDE framework applied to the ultrasonic signals. Section 3 outlines the main aspects of the cepstral-based feature extractor design and optimization. Section 4 presents relevant results that validate the feature extractor design, while section 5 discusses the feasibility of this modeling, concluding with ongoing work issues.

2. ULTRASONIC NDE FRAMEWORK

2.1. Signal acquisition and preprocessing
The specimen tested is a layered CFRP symmetric plate that consists of four layers. The damages were generated by applying free-fall impact energies, varying the mass and height to obtain five relevant damage locations. The specimen was excited by low-frequency ultrasonic burst sine-waves at a central frequency of 5 MHz, a duration of one cycle (0.2 µs) and an amplitude that amounts to 5 Vpp. Figure 1 highlights the setup of the experimental framework used to register the ultrasonic signals.

The response signal was measured at a point without damage for calibration, and the measurement procedure was repeated forty times on each undamaged and damaged locations, and registered during 30 µs, in order to generate a relevant data set. Each measurement corresponds to the resulting average of 300 captures of the signal, providing an effective reduction of the noise of the detected response signals, namely 25 dB. The measurements have been discretized at a sample frequency $f_s$ of 100 MHz/12 bits, so the corresponding
number of samples amounts to 1500.
After acquisition, the captured signals are preprocessed in order to provide a suitable representation of the ultrasonic signal. In a first step, the signals have been decimated at a sample frequency $f_s$ of 20 MHz, in order to reduce part of the noise and focus on the frequency band of interest. Then, the signals have been multiplied by a Hamming window. In our case the window is foremost used to weight the signal samples over time.

2.2. Damage detection and assessment

To design a signal processing scheme that provides a robust parametrization of the ultrasonic signals with a high discriminative capability between the different damage levels, a classification system based on cepstral distances has been developed. For an optimal use of the available data set, the training/test is performed using the one-out technique. Therefore, 39 signals are used to train a reference cepstral vector corresponding to a certain damage level, while the remaining signal is used for the test. Rotating the measurements enables us to train the system always with 39 signals, while testing it with $6 \times 40 = 240$ signals. The efficiency of the system is evaluated by defining a weighted error factor. Let the results of the test be a confusion table $R(i, j)$, with $i = 1, \ldots, 6$, where $R(i, j)$ represents the measurements number at damage level $i$ that have been classified as a damage level $j$. The weighted error factor is then defined as,

$$w_{err} \% = \frac{100 \times \sum_{i=1}^{6} \sum_{j=1}^{6} R(i, j) \cdot |i-j|}{240} \quad (1)$$

The goal of the NDE is to finally provide consistent damage information that characterizes the specimen health state. Thus, an analysis-by-synthesis scheme is applied to find the values of the damage parameters ($p$) that best fit the experimental measurements, as illustrated in Figure 2.

The reconstruction consists in the use of an iterative strategy based on the minimization of the discrepancy between the experimental and numerically predicted signals, denoted by $s^x(n)$ and $s^p(n)$, respectively. The discrepancy is represented by a residue $r$, defined as:

$$r = s^x - s^p \quad (2)$$

where $s^x$ and $s^p$ denote the feature vectors representing the signals $s^x(n)$ and $s^p(n)$, respectively. The numerical simulation of the experimental system consists in the use of a semi-analytical model of the wave interactions within the layers based on the transfer matrix formalism [9], describing the ultrasonic waves propagation in multi-layered composites. According to Lee [10], the parameters ($p$) that characterize the damage are found by a search algorithm that minimizes the cost functional $f$, by means of a least-square estimation of the residual energy:

$$(\hat{p}) = \arg \min_p f(p) \quad (3)$$

The damage parameters identification is performed according to Fahim et al. [11], assuming that the damage in each layer, respectively in each interface, is strongly correlated with a reduction of the Young modulus. Genetic algorithms [12] are applied to minimize equation 3, and provide the inverse problem optimal solution [13].

3. CEPSTRAL-BASED FEATURE EXTRACTOR DESIGN AND OPTIMIZATION

3.1. Signal windowing

First, the selection of a suitable analysis window is considered. In this case, a classical Hamming window has been applied to the ultrasonic signals. As illustrated in Figure 3, while in the original signal (left) predominates the first peak (wave front), the windowed signal (right) exhibits accentuated echoes amplitude, representative of the successive reflections of the transmitted pulse between the interface specimen/transducers.

Windowed signals are then transformed to the cepstral-domain. This work focuses on the real cepstrum $c(n)$, which is defined by means of the following expression:

$$\log |H(\omega)| = \sum_{n=-\infty}^{\infty} c(n) \cdot e^{j\omega n} \quad (4)$$

where $H(\omega)$ is the spectrum estimate. Preliminary experiments showed that the complex cepstrum do not provide any improvement,
Table 1. Weighted error obtained for several analysis windows.

<table>
<thead>
<tr>
<th>R-300</th>
<th>H-300</th>
<th>H-200</th>
<th>H-150</th>
<th>H-100</th>
</tr>
</thead>
<tbody>
<tr>
<td>SIGNAL</td>
<td>32.50</td>
<td>26.25</td>
<td>26.11</td>
<td>26.94</td>
</tr>
<tr>
<td>CR</td>
<td>12.08</td>
<td>10.41</td>
<td>9.72</td>
<td>8.88</td>
</tr>
</tbody>
</table>

while its computation is cumbersome due to the unwrapping of the digital phase. Therefore, only the real cepstrum will be considered.

In order to evaluate the effect of the analysis window and the damage discriminative capability, the following classification results have been compared: The signals obtained in the time-domain using an Euclidean distance (SIGNAL) with the ones obtained by the real cepstrum (CR) with an Euclidean (cepstral) distance using several lengths for the analysis window. Table 1 shows that the use of the Hamming windows improves the classification in comparison with the rectangular one, except for a window that amounts to 100 samples (as it cuts off the signal). As will be confirmed later, the echoes are as important as the wave front for discriminating between the different damage levels. In our case, a Hamming window that amounts to 300 samples is used to enhance the echoes.

3.2. Spectrum smoothing

It is common to restrict the Euclidean distance to \( L \) cepstral coefficients. This process is called liftering and not only allows to reduce the number of cepstral components in computations but also corresponds to a smoothing of the spectrum, preserving its spectral envelope while removing the fine spectrum information. Applying windows different from the rectangular one also allows to weight the cepstral coefficients depending on their discriminative performance. Among them, we shown that a raised-sine window can be successfully applied for damage classification using ultrasonic signals [14].

Alternatively, the spectrum can also be smoothed through signal modeling. In such a case, the ultrasonic signal is viewed as a filter output, where the spectrum estimate is given by its frequency response. In particular, autoregressive (AR) processes are considered. All-pole filters have been found to provide a sufficiently accurate representation for many types of signals in many different applications [15], where as in NDE systems, the pursued information is hidden in a random-nature signal. If an all-pole model is assumed, an LPC (linear predictive coding) spectrum estimate can be obtained.

The expected effect of using a signal modeling that follows an all-pole representation is that the cepstral distance will be less sensitive to spurious variations of the spectrum. However, there are some uncertainties regarding this modeling: Determining the order \( p \) of the LPC analysis for ultrasonics is an open issue, which do not have an intrinsic meaning as in other applications. The goodness of this modeling will depend on whether or not an AR-modeling is consistent with the way in which the data is generated.

In this work, we have evaluated the effects of smoothing over the discriminative capability of the cepstrum. Both approaches, AR modeling and liftering have been jointly tested. In order to do this, an experiment has been developed, which consists of obtaining the weighted classification error for different LPC orders and liftering window lengths. The goal is to obtain the optimal values for LPC modeling and liftering windowing for the analysis of the ultrasonic signals. The results obtained from this test are shown bidimensionally in Figure 4. Warmer (red) colors stand for high \( w_{err} \) errors while cooler (blue) ones for low errors. It must be noted that, in order to preserve the dynamic range of the color scale, weighted errors have been limited to a maximum value of 10% (as these grow up rapidly with excessively low LPC orders and/or short liftering windows).

Minimal weighted error (0.8%) is obtained with a raised-sine liftering window, whose length amounts to 28 – 29 cepstral coefficients. In contrast, the LPC prediction order seems to have a scarce relevance to achieve this minimum, provided it is high enough \((p > 20)\). Therefore, the damage parameters reconstruction will be performed with a raised-sine liftering window of 28 samples. It is worth to note that this number coincides with the echo time (in number of samples). This suggests that the cepstrum is, in some way, able to test the symmetry in the specimen (undamaged composite is symmetric). When the specimen is damaged, symmetry is usually broken, and a liftering window of echo length applied over the cepstrum is able to measure it.

4. FEATURE EXTRACTOR VALIDATION

This section aims to validate the proposed methodology. The identification of the damage distribution is assessed by considering the following assumptions:

- The damage parameters evolution is monotonically dependent on the damage level.
- Damage, such as delamination, concentrates mostly in the last interfaces, and propagates then internally and nearly symmetrically.

Therefore, the configuration pattern for the damage parameters is restricted to 3 parameters: \( p_{1} \) denotes the Young modulus of the extremity layers, \( p_{2} \) the Young modulus of the extremity interface, and \( p_{3} \) the Young modulus of the middle interface, respectively. Each parameter is defined in a dimensionless and logarithmic scale, with respect to the undamaged state.

The robustness of the analysis-by-synthesis scheme is illustrated in Figure 5, and compares the results obtained by performing the optimization directly on the time-domain signals with the ones obtained when the aforementioned cepstral parametrization is applied. The damage correlation parameters are plotted against the impact energy values. Each box has lines at the median value (red), at the
lower and upper quartile values (blue), and whiskers at the minimum and maximum values (black). Outliers are represented by a red cross. In these plots a consistent decrease on the elastic modulus is expected as the damage energy increases.

It results that the optimization performed in the cepstral-domain leads to a more consistent damage evolution than the one delivered by the time-domain solution. The reduced set of cepstral features improves the statistical distribution of the damage parameters: (1) The variability of the damage parameters at each damage level is drastically reduced. (2) The median values of the damage parameters consistently decrease while increasing the damage level. A careful interpretation allows to observe that delamination ($p_2$) occurs at early stage of the impact energy and increases with the damage level, while delamination ($p_3$) occurs at some later stage of the impact energy, validating the aforementioned hypothesis.

5. CONCLUSIONS

This study shows the capability of the real LPC cepstrum to discriminate the damage level of a CFRP plate subjected to different impact energies. The discriminative performance of the proposed parametrization has been evaluated by a system based on cepstral distances that recognized the concrete damage level corresponding to a given test signal, leading to the following conclusions: (1) It has been demonstrated that it is necessary to include the wave echoes to perform the analysis. Consequently, they may be enhanced using a suitable analysis window. (2) The cepstrum is an appropriated domain to perform a feature extraction. This study has presented a cepstral coefficients selection based on the use of a simple filtering window with the appropriate size, corresponding to the echo time. Ongoing works may include the study of advanced extraction/selection techniques such as discriminative transformations of the feature space (LDA or PCA).

Finally, the cepstral parametrization has been inserted in a analysis-by-synthesis scheme, and allowed us to reconstruct consistently the damage parameters corresponding to different impact energies.

6. REFERENCES