Detecting Delaminations in Composites through Active Wave Modulation Spectroscopy: Analytical Investigation of Critical Nonlinear Mechanisms

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Abstract

The present work aims to address open issues hindering the development of nonlinear wave modulation SHM/NDE methods for the detection of delaminations in composite laminates. Specifically, the mechanisms generating the nonlinear indices are clarified and the relationship of the latter with damage and wave parameters is investigated. A robust and computationally fast time domain spectral finite element containing high-order layerwise laminate mechanics is further extended to model delaminated composite strips. Contact mechanisms enabling impacts between the delaminated interfaces are included in the formulation. Simulations of high-frequency antisymmetric and symmetric ultrasonic wave propagation in Carbon/Epoxy strips with various delaminations sizes are presented. The simulations reveal complex nonlinear phenomena involving interactions between wave conversion and contacts in the delaminated region, which subsequently result in frequency harmonics in the dynamic response, manifesting the presence of delamination. The dependence of the generated harmonics and their modulation factor, to the type of assumed contact, the size of damage and the frequency/wavelength of the excited wave are further studied.

Keywords. Guided waves, Composite Materials, Delamination, Contact mechanics

1. Introduction

The last decades, early damage detection in composite materials is the main motivation of the researchers. Various methodologies have been reported, studied and extensively analysed. Among them, very promising appears to be the detection of composite materials damage using nonlinear methodologies, based on the active detection of the damage in the tested structure as summarized by Jhang 2009\(^1\) and Giurgiutiu et al 2011\(^2\). The damage reveals itself in various ways like the creation of sub-harmonics, the generation of nonlinear phenomena like the shifting of modal frequencies\(^3\)\(^-\)\(^5\) or the mixing of frequency response and the creation of additional harmonics (sidebands), due to interaction of the propagated wave with nonlinear phenomena at the crack faces. These phenomena are very weak in intact structures and remarkably strong in the damaged ones. The sensitivity of nonlinear methodologies in damage detection is far greater compared with the linear wave propagation, as they combine the sensitivity of damage detection through the nonlinear interactions with the large inspection area capability provided by the guided Lamb waves. One of the simpler and more popular methodologies to monitor the damage presence is based on the appearance of additional harmonics (sidebands) in the frequency response.
of the propagated wave. These nonlinear interactions manifest themselves with a wave modulation of the propagated ultrasonic signal. Many experimental studies state that these are due to the critical crack oscillation modes; the crack opening, the friction between the crack faces and the normal out of phase vibration of the crack edges during the global structural vibration. From the experimental aspect of view, this methodology was mainly applied to detect cracks in metallic structures, aircraft parts, adhesive joints between metallic components and other applications. However, one demanding emerging area of SHM is the detection of damage in composite structures like aircraft and wind-energy blades etc. During the last decade research work has been focused on the application of the wave modulation spectroscopy methodologies for the detection of damage in composite materials and their transition to permanent SHM techniques. However, instead of the various experimental approaches based on the SHM via the application of non-linear methodologies and their obvious effectiveness very few works have been published relative to the mechanisms generating these damage indices. Shen and Giurgiutiu analytically studied the mechanisms acting locally at the damage region, when an ultrasonic wave is propagated in the examined structure, creating these nonlinear damage indices. Focusing our review on composite structures and among the various types of damage to the delamination crack Shkerdin and Glorieux modelled the nonlinear interaction between high frequency Lamb waves and bilayer isotropic materials containing a delamination, using a quasi-stationary approach. However, there is limited reported numerical research elucidating the involved key nonlinear mechanisms and relating the delamination characteristics to the measured nonlinear indices. More importantly, experimental work conducted by the authors has shown strong non-monotonic dependence of nonlinear modulation effects and damage indices to the frequency and wave type of the ultrasonic wave. The limited knowledge in the previous topics and in particular the relation of damage indices to damage size and wave characteristics, hinder the development of nonlinear SHM methods based on active nonlinear wave modulation.

The purpose of current paper is the investigation of the mechanisms, which enable the appearance of harmonics of the carrier ultrasonic frequency with the presence of damage. Among the various types of damage, this work focuses on the delamination cracks between two adjacent layers of a composite laminate. Layerwise mechanics are applied for the through thickness approximations and the delamination is introduced as discontinuity in the displacement field. The contact between the two damaged faces is modelled locally using a contact law for the indentation of cylindrical impactor in composite laminates. The above laminate mechanics are encompassed in an explicit time domain spectral finite element for composite strips which provides demonstrated capability for very fast and accurate simulations of guided waves in laminated composite structures. Simulations investigate the model efficiency to describe the nonlinear interactions taking place at the damage area. Apparent objective is to identify the ideal actuation frequency, which will maximize the sensitivity of the method, and conversely to relate the size of damage to the measured nonlinear wave response.

2. Cubic Spline Layerwise Theory (CSLT) with Delamination

In this section is described the ability of the developed layerwise mechanics regarding the modelling of delamination. The structure and philosophy of the aforementioned
A numerical tool\(^\text{17}\) makes the insertion of delamination very feasible, just by not applying the field variable continuity at the delaminated section and adding an additional degree of freedom at each direction \((u, w)\). Figure 1a. That is, the common DOFs of the interface will be set free, Figure 1b.

\[
\begin{align*}
\text{Figure 1 Approximation of displacement field and layerwise expansion of CSLT with a two DL configuration; (a) continuity of displacements across layer interfaces is self-satisfied for the case of two distinctive consequent DLs; (b) continuity of displacements across layer interfaces is selectively neglected for the case of two delaminated distinctive consequent DLs}.
\end{align*}
\]

### 2.1 Contact assumptions

A very interesting finding by the authors, is that when within the delaminated faces are applied forces due to the indentation of each other, certain nonlinearities appear\(^\text{18,19}\). The authors, by exploiting to the maximum the capabilities of the numerical tool proposed a contact method which combines the contact law for impact in thin supported laminates\(^\text{20}\) and the approximated contact stiffness of two consequent interfaces under contact by Turon et al.\(^\text{21}\).

The assumption that enables the contact between the two interfaces, is that the bottom delaminated face tries to indent the upper face upon contact, therefore each node in the interface is considered to act as an individual cylindrical impactor, with a radius \((r_i)\) illustrated in Figure 2. In addition, the contact is established when the difference of the vertical displacement (indentation) of two facing nodes reaches zero or negative value (i.e. \(w_b-w_t \leq 0\)), where \(w_b\) and \(w_t\) are the respective vertical displacements of the bottom and top faces.
Figure 2 Contact assumptions between two delaminated faces, with each node acting as an individual impactor with its respective radius.

The resulted contact force between two nodes is calculated through the following equation

\[ F_{c_i} = C_{s_i} w_i^2 \]  

where \( C_{s_i} \) and \( w_i \) are the contact stiffness and the indentation of each pair node. The contact stiffness is calculated by the following equation

\[ C_{s_i} = \frac{\alpha (\pi E^* r_i)}{h} \]  

Where \( \alpha \) is a very large parameter which found to converge between 5000 and 10000, \( E^* \) is the contact modulus between an indentor and a semi-infinite laminate, \( r_i \) is the radius of the impactor and \( h \) is the thickness of the top delaminated face.

After a close investigation of the response of a delaminated strip formulated with contact mechanics between the delaminated interfaces, has been observed that full compatibility of the normal displacements between the contacted interfaces ought to have been applied. At this point it should be mentioned that the kinematic assumptions of the laminate mechanics assume also as DOFs the rotations of the respected displacements \((u, w)\), eq.(4) . In order to fully achieve the compatibility of the transverse displacement, an interaction through the respective equivalent moment should be applied between the DOFs \( d^i_k \) of the bottom delaminated face and \( d^1_k \) of the top delaminated face. The resulted torque is calculated as follows

\[ T_{c_i} = \beta F_{c_i} r_i \]  

where \( \beta \) is a parameter and is equal to \( \alpha/100 \). Kinematic assumptions can be written as

\[ u_k(x, \zeta, t) = u^i_k(x, t) \cdot \psi^i(\zeta) + u^2_k(x, t) \cdot \psi^2(\zeta) + b^1_k(x, t) \cdot \frac{h_k}{2} \psi^2(\zeta) + b^2_k(x, t) \cdot \frac{h_k}{2} \psi^4(\zeta) \]  

\[ w_k(x, \zeta, t) = w^i_k(x, t) \cdot \psi^i(\zeta) + w^2_k(x, t) \cdot \psi^2(\zeta) + d^1_k(x, t) \cdot \frac{h_k}{2} \psi^2(\zeta) + d^2_k(x, t) \cdot \frac{h_k}{2} \psi^4(\zeta) \]  

where subscript \( k \) indicates the discrete layer, superscript \( i = 1, 2 \) denotes the bottom and top surfaces of a discrete layer, and \( \psi^i(\zeta) \) are Hermite polynomial splines, \( \zeta = 2(z - z_k)/h_k \) is the non-dimensional thickness variable in a \( h_k \) discrete layer, \( z \in [z_k, z_k + h_k] \) and \( h_k \) is the discrete layer thickness. The last integrated interaction of the contact assumptions is a static friction applied at the axial displacement DOFs, eq. (4).
\[ SF_i = \gamma \mu Fc_i \]  

where \( \gamma = \alpha / 1000 \) and \( \mu \) is the static friction coefficient taken from the bibliography\(^2\) equal to 0.38.

### 2.2 Time domain spectral finite element

The kinematic assumptions presented in the previous section are used as a foundation for developing a strip finite element with \( C_0 \) Lagrange shape functions. Exploitation of high order Lagrangian polynomial shape functions ensures the efficient spatial approximation of high wavenumbers in the plane of the strip. The nodes of the proposed element are located at Gauss-Lobatto-Legendre (GLL) integration points provided as solutions of the equation,

\[ (1 - \xi_i^2) \cdot P_{n, \xi} (\xi_i) = 0 \]  

where, \(-1 \leq \xi \leq 1\) is the local coordinate of the element. Collocation of nodes with GLL integration points leads to diagonal or near diagonal mass matrices, which boost the speed of time integration.

### 3. Results

The efficiency of the aforementioned theories is demonstrated through representative examples. In all cases, a laminated SIGRATEX CE 8912-170-36 Carbon/Epoxy composite strip was considered, material properties taken from characterization tests conducted in the Lab.

<table>
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<th>Value</th>
<th>Units</th>
<th>Quantity</th>
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</tr>
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Numerical simulations were performed on a strip 0.4m long and 0.002m thick. Relative to the damage, two different delamination lengths were studied, having length 0.02 and 0.04 m and covering the 5 and 10% of the total strip length respectively. The location of the delamination was at the middle of the strip length and thickness. The strip was simulated under clamped-free boundary conditions. Schematic illustration of the strip is presented in Figure 3.

As the objective of our study was to investigate the propagation of symmetric waves along the strips, two sinusoidal waves were excited at various frequencies, 0.1m from strip free edge. Both the sinusoidal waves were in phase and applied at the bottom and top faces (Figure 3) in order to generate symmetric guided waves. Measured response was the transverse displacement of the node located at 0.1m from the strip fixed edge.
3.1 Delamination with and without contact

The first study deals with the contribution of the contact mechanics at the modelling of a delamination crack. Considering that, a symmetric wave is propagated in the composite laminate having 40 mm delamination crack, the inclusion of delamination in the numerical formulation, in the manner it was described in the previous section, without the presence of interfacial contact results on lack of sensitivity between the healthy and delaminated structure. Examining Figure 4 it is obvious that the two frequency responses of the healthy and the delaminated laminate provide the same response.

The next step of the study is the in depth observation of the interactions taking place at the damage interfaces. The normal displacements (w) of the top and bottom face of the laminate are illustrated in Figure 5. Two snapshots are presented in this figure (a) is the response of the healthy strip, and (b) is the response of the delaminated without the inclusion of the interfacial contact mechanisms. Both snapshots refer at 0.551ms after the start of the wave generation providing enough numerical time, for the wave to propagate through the delamination. Also, the wave excitation point is clearly indicated, 0.1m away from the strip free edge. In Figure 5 (a) the propagation of the symmetric S₀ mode is clearly illustrated. However, in Figure 5 (a) the region and the exact extents of the
delamination are clearly visible. The important observation is the mode conversion that takes place locally at the damage area as the \( S_0 \) mode converts to \( A_0 \). Also, it is important to mention that, the \( S_0 \) frequency appearing at the figure refers to the \( S_0 \) mode calculated for the composite laminate with the full thickness. In contrary, as due to the presence of delamination, the laminate is divided into two sub-laminates the \( A_0 \) has the frequency that refers to the propagation of an antisymmetric \( A_0 \) mode through the top half of the laminate. However, this strong evidence of the damage presence is visible and detectable only locally at the damage area. Moving at the measuring position of Figure 4, 0.1m away from the fixed strip end, there is no difference captured between the two snapshots of the intact and the delaminated strip. This observation clarifies the lack of sensitivity captured at this point.

The simulations illustrated in Figure 6 present the analytical model efficiency when the model has a more realistic behaviour with contact applied between the delamination faces. Both figures correlate the variation of the normal displacement \((w)\) across the strip length between the healthy and the delaminated strip (a) without the presence of interfacial contact and (b) with contact mechanisms. As presented in Figure 6 (a) simulations present that the fundamental antisymmetric is trapped inside the delamination area, not being able to propagate to the rest of the strip. On the other hand, in Figure 6 (b) is obvious that as the fundamental \( S_0 \) wave passes through the delaminated region and is converted to \( A_0 \). By inserting the contact mechanics, is granted a mean of “escape” to \( A_0 \) and the two modes coexist with the \( S_0 \) acting as a carrier mode to the \( A_0 \).

Figure 5 Snapshot of a carbon/epoxy [0/90]s strip under sinusoidal symmetric excitation with central frequency at 31.37 kHz at 0.551 ms; (a) Pristine specimen; (b) Delaminated specimen.
3.2 Non linear response signatures –Damage index.

As described in the introduction main objective of our study is the simulation of the non-linear indices, like the harmonics appearing in the frequency response. These harmonics appear in intervals equal to the carrier ultrasonic frequency and are an evidence of the presence of non-linearity in the structure probably due to the presence of damage. Figure 7 (a) to (d) present the frequency content of the normal displacement (w) response as this is simulated at the measuring point (0.1m away from the fixed end) due to the symmetric wave excitation at the excitation point (0.1m away from the free end). Both actuation and measuring locations are away from the delamination region. Simulations are performed with the model that considers contact mechanisms at the damage area. Four different actuation frequencies were selected; 8.2, 11.8, 31.3 and 192.9 kHz and they are presented respectively in each of Figure 7 subfigure. Each of them was selected according to the $A_0$ propagation wavelength in the composite laminate, which is 0.03, 0.025, 0.015 and 0.005m respectively.

The first important conclusion is that for the three higher frequencies the simulations capture a clear pattern of harmonics appearing in intervals equal to the ultrasonic carrier frequency. This points out the numerical model efficiency to simulate this non linear index extensively used as a damage detection evidence. In some of the plots i.e. in (b) the
pattern of sidebands appears stronger for the small delamination length, while in (c) the bigger delamination length seems to be more evident. In (d) both delamination sizes reveal their presence, while in the (a) there is no pattern of sidebands simulated. This variation appearing in the harmonics presence as the frequency and wavelength of the propagated wave varies, indicates the significance to extract a relationship between these parameters.

In order to study the aforementioned findings, the authors performed various analyses. Ten validation cases were selected for pristine and delaminated strips trying to correlate the wavelength of the propagated wave with the simulated delamination length. We introduce a damage index, \(I_d\), as the ratio of the amplitude of the 1st harmonic over the amplitude of the carrier frequency peak. Figure 8 illustrates the variation of the damage index versus the ratio of the wavelength of the propagated wave over the delamination length. There are two sub-plots, the left for the 2cm delamination length and the right for the 4 cm damage. Additionally, the \(A_0\) curve is illustrated providing a continuous correlation of the antisymmetric wavelength with the propagation frequency. These plots present that there are some peaks captured in the variation of the \(I_d\) and they are related with some of the cases presented in Figure 7. For instance, when the excitation frequency is set at 192.9KHz a peak is captured on both plots for wavelengths ratios 0.25 and 0.125 respectively. Similar conclusions are extracted for the rest of the cases presented above. However, there is no clear conclusion extracted, relating the wavelength of the propagated wave with the harmonics presence sensitivity. This study seems promising to reveal the non-linear mechanisms and interactions taking place in the damage area but requires further investigation.
Figure 7 Frequency content of the simulated normal displacement as a function of frequency. Excitation at (a) 8.29, (b) 11.8, (c) 31.3 and (d) 192.9KHz.

Figure 8 Variation of the Damage Index $\iota_d$ as a function of the ratio of the propagated wavelength vs the existed delamination length, (left) 2cm delamination and (right) 4 cm delamination.
4. Conclusions

The paper presented an analytical and numerical investigation of the mechanisms responsible for the generation of the non linear indices frequently used as evidences for the presence of damage in various SHM methodologies. Through the laminate thickness the modelling of delamination debonding was performed with the help of a layerwise TDSFE and the kinematics facilitated the procedure by selectively neglecting the field variable continuity of the displacements. Furthermore, a contact law was incorporated in order to provide a more realistic aspect to the developed analytical tool. In this manner, the explicit TDSFE model is capable to describe the contact nonlinearities in the damage area, and their relation to wave and damage characteristics.

The numerical simulations, clearly illustrate that the admission of contact the delamination faces is the key factor for the prediction of harmonic frequency sidebands in the dynamic response. The observed conversion of the fundamental symmetric mode to a fundamental antisymmetric mode in the delamination zone had an important effect on the developed super harmonics. It was observed that when the contact mechanics were enabled, the $A_0$ mode was no more confined in the delaminated area, but its contacts generated antisymmetric waves, which were propagating along the strip coexisting with the $S_0$ mode. The aforementioned propagation of $A_0$ waves outside of the delamination crack is the source of the generated sidebands in the FFT plots and the indicator of delamination cracks.

Additionally, a modulation factor was introduced as damage index. This dependence of index as a function of the propagated wavelength was studied for various damage sizes. It was found that the modulation factor is more sensitive to certain values of guided wave frequencies and wavenumbers. It remains a topic of further study to provide a robust relation between the excitation frequency and the modification factor. Future work will also include experimental duplication of the attained numerical results.

References