Critical Parameters of Impact Damage Detection in Composite Plates Using an Active Nonlinear Acousto-Ultrasonic Piezoceramic Sensor

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ABSTRACT

This paper investigates the potential of an active nonlinear ultrasonics SHM methodology to reveal impact damage created in Glass/ Epoxy composite plates under cantilever support conditions. For the experimental procedure electromechanical shaker and piezoelectric devices are simultaneously used to provide the low and high frequency excitation signals respectively, while for the acquisition of the mixed signal a piezoelectric wafer is used. Nonlinearities induced at the high-frequency signal, such as sidebands at the spectral components, as well as, the modulation factor of the sensory voltage are evaluated as damage indicators. Experimental results quantify the potential of the method in detecting impact created under very low energy level impact loading. The obtained results finally show that the active nonlinear wave modulation SHM method can work in the case of realistic (clamped) supports.

INTRODUCTION

Composite materials are nowadays extensively used in aeronautical structures. Among the various types of damage which may easily occur, remain hidden and propagate catastrophically in a composite structure is foreign body impact damage, therefore, early detection and monitoring of impact damage is highly desirable. Non-linear ultrasonic NDE techniques are newly developed methodologies which are reported to provide high sensitivity in the detection of small crack damage. However, little work has been reported on the application of non linear ultrasonics for damage detection in composite structures; moreover, the reported techniques are suitable for non destructive inspection, and not for permanent structural health monitoring. A nonlinear active SHM methodology application based on the usage of piezoelectric actuators and sensors has been reported by the authors and applied to the detection of damage in composites [17-19]. A major issue concerning the potential of nonlinear wave modulation methods remains the effect of supporting conditions [20]. This paper aims to address this issue, and investigates experimentally the potential of non-linear acousto-ultrasonic modulation methods to detect impact damage in composite plates subject to various supporting conditions.

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The exploitation of nonlinear vibro-acoustic effects for diagnostics and, in particular, for early crack detection is an emerging NDE field, which is rapidly progressing after pioneering encouraging results [3-4]. Due to material or damage induced nonlinearity, a wave can distort, creating accompanying harmonics, multiplication of waves of different frequencies, and, under resonance conditions, changes in resonance frequencies as a function of the driving amplitude. In undamaged materials, these phenomena are very weak, while in damaged materials, they are remarkably strong. The sensitivity of nonlinear methods to the detection of damage (cracks, flaws, etc.) seems far greater than that of linear acousto-ultrasonic methods (measures of wave speed, attenuation and dissipation), and in fact, these methods appear to be more sensitive than any method currently available [5-7].

A widely used methodology is based on monitoring nonlinear wave mixing in the material [8-13]. Two excitation signals are used, resulting in the modulation of the weaker wave under the action of a strong low-frequency wave or vibration. The manifestations of the non linear modulation appear as wave distortion and generation of additional harmonics (sidebands). Non linear wave modulation techniques are widely used to detect crack in metallic structures [10], machine components and aircraft parts [9], adhesive joints [12] and polymers [13]. The majority of reported work using non linear wave modulation methodologies is focused on the detection of cracks in metals and very little work is reported on the detection of composite damage, such as matrix cracks in composite materials [14] and delaminations between composite structure and piezoelectric wafers [13]. The bulk of reported experimental setups implement NDE transmitters and receivers for the ultrasonic carrier wave, and to generate non-linearities under the low frequency excitation implement impact hammers, mechanical actuators [10], and speakers. Ref. 11 utilizes piezoceramic wafers for the ultrasonic wave and a piezostack actuator for the low frequency wave to detect cracks in metals.

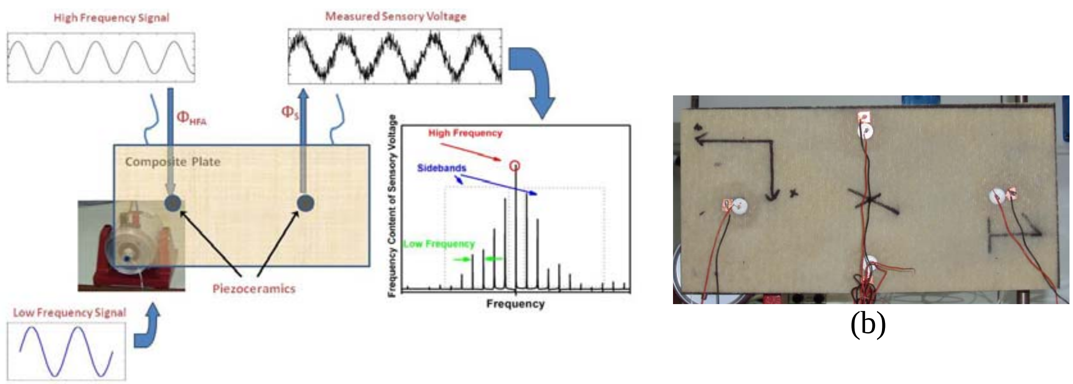
To our best knowledge, very little work has been done in the area of damage detection in composite structures using nonlinear ultrasonic methodologies. Previous works by the authors investigated the ability of methodology to reveal delamination cracks, matrix cracking and low velocity impact damage [17-19]. However, in each of the previous works free supporting conditions were used in order to eliminate non linearities introduced to the tested system due to supports. The current paper investigates a critical parameter which is reported [20] to affect the methodology sensitivity, that is, the boundary conditions.

The following sections describe tests contacted on Glass/Epoxy composite plates subjected to low energy impact loading, while for comparison purposes additional experiments were contacted on a second baseline composite plate. For the nonlinear excitation of all plates, an electromechanical shaker was used combined with a d_{31} piezoceramic wafer for the generation of the high-frequency carrier wave, while for the signal acquisition another piezoceramic sensor was used. Plates were tested under free and cantilever supported conditions. Generated damage after very low energy impacts, developed nonlinearities which for both supporting conditions cases is clearly manifested as sideband spectral components at the two sides of the central carrier peak of the ultrasonic wave. Various ultrasonic frequency levels are applied for the high frequency excitation carrier signal and the sensitivity of the methodology on the carrier wave frequency is extensively investigated. Damage indexes are proposed and investigated and conclusions about the potential of method are presented.

MATERIALS AND EXPERIMENTAL SETUP

Materials and Loads

Glass-fiber/epoxy (GFRP) laminated plates were fabricated using eight layers of glass UD fabric in epoxy resin. Each of the plates had dimensions 300x150mm, 2mm thickness and $[0_2/90_2]_S$ lamination configuration. In order to create impact damage in the composite laminate, one of the plates was subjected under low velocity impact. The impact was applied via a fully controlled INSTRON impact machine (drop tower). The impactor applied exactly at the centre of the composite plate, which was supported under simply supporting conditions. The characteristics of the impactor were: energy level 4J, impactor mass: 16.8Kg, impact velocity: 0.69 m/sec, and initial impactor height: 0.0242m. Due to the tested plates lamination configuration and the applied impact energy level of the impactor, initially matrix cracks are expected to be generated, converted into delamination cracks at the interface between the 90 and the 0 degrees ply. However, C-SCAN tests revealed no delamination damage.



(b)

(a)

Figure 1. (a) Experimental setup and (b) Glass/Epoxy composite plate with two pairs of piezoceramic wafers attached.

The Nonlinear Ultrasonics Methodology

The concept of Nonlinear Acousto-Ultrasonic Methodology considered in this work is shown in Figure 1a. The excitation setup consisted from an electromechanical shaker and a piezoceramic wafer, while the propagated waves are acquired via a second piezoceramic wafer acting as sensor. Both the wafers were permanently epoxied on the plate specimen surface. The low frequency actuator (LFA) was a small (6 lbs) electromechanical shaker attached at the illustrated position on the tested structure. A Labview visual instrument was used to generate the digital sinusoidal waveform, which was subsequently converted to analog using a National Instruments 16-Bit DAQ board, further amplified using an appropriate LDS amplifier and finally driven at the electromechanical shaker. The frequency level of the LFA was set approximately at the modal frequencies of the tested structure. A piezoceramic circular wafer with 12mm radius and 0.9mm thickness, termed thereafter as high frequency actuator (HFA), provided the carrier frequency (Figure 1b). The applied signal on the HFA was a sine wave at ultrasonic frequency, always having amplitude of 10Volts. The ultrasonic sine wave signal was generated and applied directly on the specimen using a Physical Acoustics 14-bit arbitrary waveform generator card. Both actuations were simultaneously applied on the respective plate. The response signal at the piezoceramic sensor was attenuated and then acquired and digitized via a high speed 24-bit National Instruments DAQ board. A visual instrument developed in Labview was used to extract the frequency content of the measured sensor response. As expected from previous work [19] the sensitivity of the method is drastically increased when the carrier ultrasonic wave propagates in a direction vertical to the direction of matrix cracks (Fig. 2a), For this reason two piezoceramic actuator/sensor pairs of were used to generate and acquire the ultrasonic carrier wave, as illustrated in Fig 2b. Plates were tested under cantilever (clamped-free-free-free) supporting conditions, clamped at one of the short edges as illustrated in Fig. 2c.

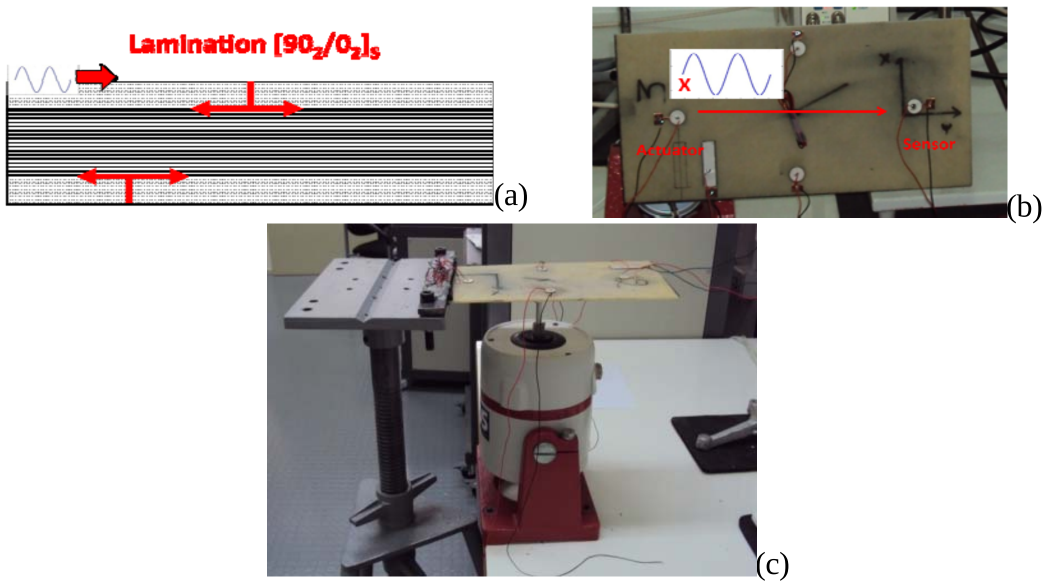


Figure 2. Experimental procedure (a) Possible generated damage in the composite plate due to impact vs wave propagation (b) Used pair of piezoceramics and (c) Cantilever experimental setup.

RESULTS AND DISCUSSION

Wave Modulation Spectroscopy.

The non linear ultrasonic SHM methodology described above was applied for the detection of the impact damage generated into composite plates. The frequency of the signal applied on the low frequency actuator (electromechanical shaker) was set approximately at 200Hz, equal to one of the modal frequencies of the cantilevered composite plate. The frequency of the carrier excitation sinusoidal signal, applied at the terminals of the HFA piezoceramic actuator, was in the range between 20 and 300 KHz. Representative plots are illustrated in Figs 3a to 3f, presenting the acquired sensor response for three different carrier frequencies applied at the HFA actuator pair for two specimens, one “healthy” baseline and one subjected to low velocity impact.

Measurements of the specimens subjected to impact loading illustrate clear sideband spectral components at both sides of the central carrier frequency. These spectral components appear in intervals equal to the applied LFA actuation (200Hz) and manifest themselves as damage indicators. Current results enforce the efficiency of the used methodology and are a critical add-on to previous work [19]. Previous results indicated the ability of the methodology to reveal the presence of damage under free supporting conditions in case the ultrasonic carrier wave was propagated in a direction vertical to the fiber orientation of the outer ply.

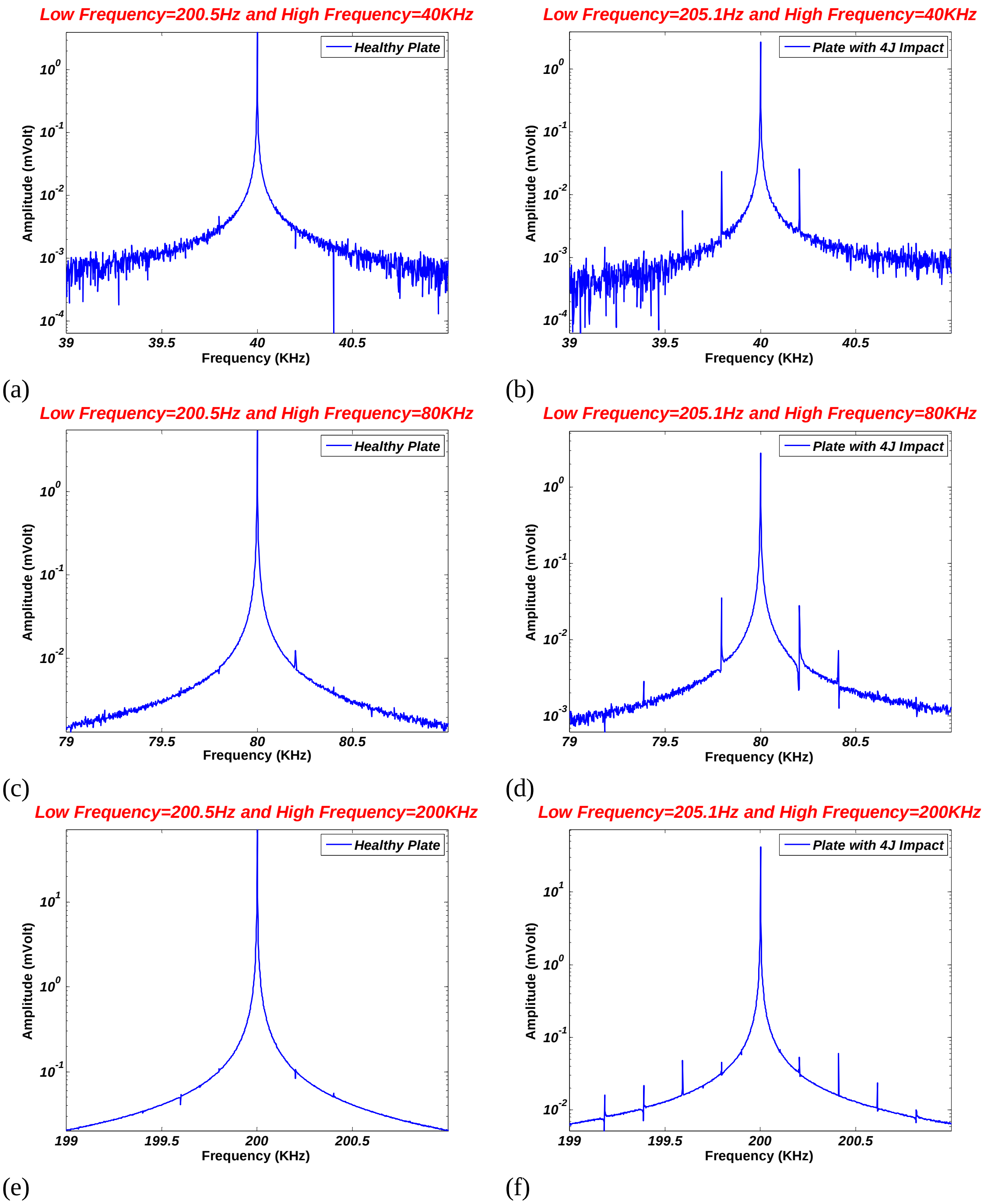


Figure 3. Spectral components of the sensor signal measured in a healthy (left) and a damaged (right) plate for various frequency values of ultrasonic carrier waves applied at the HFA. (a-b) 40KHz; (c-d) 80KHz;) (e-f) 200 KHz. The damaged plate was subjected to 4J impact load.

A similar or higher sensitivity is revealed in Fig 3, corresponding to measurements under a more realistic experimental setup, and it is an evidence of the used methodology efficiency. It is also critical to mention that only very small and weak sideband components appear in the healthy plate, strengthening one critical advantage of wave modulation spectroscopy, the elimination of a healthy baseline measurement.

Introduction of Damage Indexes

Two damage indexes are additionally introduced, in order to provide a more clear damage indicator. In the first case the modulation factor is extracted from the experimental measurements of both the healthy and the impacted plate and is expressed in Eq 1.

$$DI_4 = \frac{|V_s(f_L)|}{|V_s(f_H)|} \qquad (1)$$

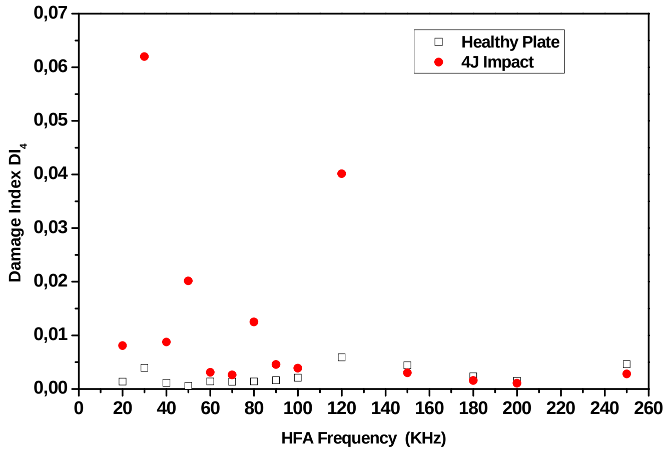


Figure 4. Variation of modulation factor DI_4 as a function of the applied HFA actuation.

This damage index correlates the measured amplitude of the central carrier frequency f_H and the amplitude of the 1st left hand sideband spectral component f_L. Fig. 4 presents the variation of the damage index, as a function of the applied frequency at HFA the piezoceramic actuator, in the range of 20 to 250 KHz, with LFA actuation at 200Hz. From the variation of the modulation factor becomes clear that measurements of the healthy specimen remain insensitive and close to zero. On the other hand, notable increase is captured in the modulation factor of the specimen subjected to impact damage manifesting the damage presence.

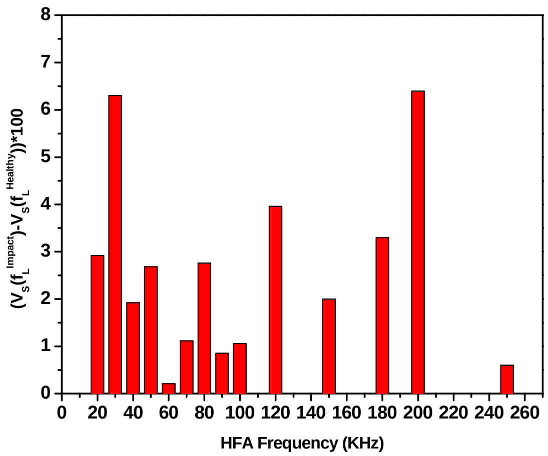


Figure 5. Variation of the damage index DI_5.

A second damage indicator is also introduced and expressed in Eq. (2). This is the difference of the measured amplitude of the 1st left-hand sideband spectral component between the damaged and healthy plate.

$$DI_5 = \left[V_S\left(f_L^{Impact}\right) - V_S\left(f_L^{Healthy}\right)\right]\cdot 100 \qquad (2)$$

Fig. 5 shows the significant variation of DI_5 with the applied carrier wave frequency, revealing the presence of damage in the composite plate. Prior experimental measurements [19] have also illustrated the ability to reveal the presence of damage in free plates. However, the testing of specimens under cantilever support conditions provides a more realistic structural system, as additional non linearities are introduced to the system due to supports. Another important conclusion is, that apart from the drastic increases to the damage indices observed in some HFA frequencies a; in general they remained sensitive for most frequency values applied on the HFA actuator.

CONCLUSIONS

In this paper experimental work on impact damage detection in composite plates was presented using a new non-linear ultrasonic SHM methodology with in-situ piezoceramic actuators and sensors. Glass/epoxy composite plates were fabricated and subjected under 4J low energy impact loading. An additional unloaded plate was used during the experimental procedure to provide the baseline measurements. Each of the plates was tested under cantilever support conditions while the HFA actuation varied in the range between 20 and 250 KHz.

Extracted measurements presented the sensitivity of the method to reveal the presence of damage illustrating a clear pattern of sidebands at the two sides of the central carrier frequency. Finally two damage indices were introduced based on the measured amplitude of the sidebands and the central carrier frequency. These indices were very sensitive to reveal the presence of damage in all the range of the applied HFA actuation. In closing, the present work shows that the active nonlinear wave modulation SHM method can work in the case of realistic (clamped) supports. Future work will address the effectiveness of the method in cases of higher energy impacts and imperfect supports.

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