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2015 J. Phys.: Conf. Ser. 628 012103

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Analysis of elastic nonlinearity for impact damage detection in composite laminates

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Abstract. This paper concerns the experimental analysis of nonlinear response features of a composite laminate plate for impact damage detection. The measurement procedure is based on the Scaling Subtraction Method (SSM) and consists in exciting the damaged specimen with two sinusoidal signals at different amplitude. The linearly rescaled response signal at low amplitude excitation is subtracted from the response at large amplitude excitation to extract the nonlinear signatures. The latter are analysed in the time domain to infer the presence of damage. Results are compared with frequency domain analyses using the nonlinear vibro-acoustic modulation technique (NWMS). Changes in amplitude and phase as well as modulation effects of the acquired responses are also monitored. Surface-bonded, low profile piezoceramic transducers are used for excitation and sensing. Both measurements techniques are applied to detect barely visible impact damage in laminate composite plate. Non-destructive penetrant-enhanced X-ray inspections are carried out to characterize the extent of internal damage. The behavior of the nonlinear features and the sensitivity of each technique are also investigated in the paper.

1. Introduction

Non-destructive evaluation techniques (NDE) are commonly adopted to assess structural integrity. Among them, the NDE methods based on ultrasounds are very successful in detecting structural damage, owing to the close relation between wave propagation and material properties. In recent years there has been an increasing interest in methods which investigate the nonlinear acoustic response of materials [1]. The sensitivity shown by such techniques is of particular interest when composite materials, which are typically susceptible to impact damage, are concerned. The nonlinear acoustic phenomena affecting the elastic response to dynamic excitations are related to material anharmonicity and can be radically enhanced by the presence of small defects, micro cracks or surfaces in friction. Resonance frequency shift, higher/sub harmonic generation, modulation of elastic waves are just some of the experimentally observed effects that reveal the presence of damage. Although different theoretical models (classical nonlinear theory of elasticity, contact acoustic nonlinearity models or hysteretic models) have been proposed to explain the generation of nonlinear effects, the physical mechanism behind these experimental evidences is still a matter of scientific debate [2].

In general, the nonlinear acoustic techniques take into consideration some particular features of the nonlinear elastic response such as higher harmonics or modulation sidebands, whilst they neglect other



aspects such as amplitude nonlinearities occurring at the fundamental frequency. Due to the slight variations that may typically occur between intact and damaged case, especially when considering early damage stages, these methods are often effective only in laboratory environments. Other limitations may also come from intrinsic material nonlinearities, boundary conditions and inherent nonlinearities related to the acquisition instruments.

A new nonlinear ultrasound technique, relying on nonlinear effects such as amplitude attenuation and phase delay at the fundamental frequency has been recently proposed [3] as a valid alternative to traditional frequency domain techniques. Referred to as Scaling Subtraction Method (SSM), it is based on the assumption that the nonlinearities related to cracks and material defects break the proportionality between excitation and response of the structure. This nonlinear contribution is negligible for low amplitude excitations and becomes progressively more significant as the amplitude of the excitation increases. Based on this assumption, some damage indicators are introduced in [3] to identify the nonlinearities related to the damage. The SSM technique has been experimentally applied to characterize the behaviour of materials with different degree of nonlinearities (lead, steel, mortar, concrete) [4] and to describe damage evolution [5].

This paper presents an application of the SSM to detect barely visible impact damage in a composite laminate plate. The specimen was analysed in both intact and damaged conditions. Non-destructive penetrant-enhanced X-ray inspections were also performed to identify and characterize internal damage. Surface bonded, low profile piezoceramic transducers were used in the test both to excite the plate with sinusoidal signals at different amplitudes and to acquire the response in different points. The SSM damage indicators are analysed in the time domain and then compared with the results of a frequency domain analysis carried out with the Nonlinear Acoustic Wave Modulation technique (NWMS) [6,7,8]. The layout of the paper is as follows. The SSM and NWMS approaches for damage detection are briefly introduced in section 2. Section 3 describes the experimental procedures adopted in the tests. Damage detection results are provided in section 4 and the paper is concluded in section 5.

2. Scaling Subtraction Method and Nonlinear Acoustic Wave Modulation Technique

The idea behind the SSM is that the nonlinear contribution related to the damage begins to show its effects only when the amount of energy transferred to the sample reaches a certain value [4]. It follows that low amplitude excitation signals do not have sufficient energy to excite nonlinearities and the corresponding output signal is expected to be equivalent to the one obtained from an intact structure. Damage is typically defined as a change introduced into a material that adversely influences its parameters. In particular, discontinuity (like crack or delamination) introduces nonlinearity into a material, therefore the analysis of nonlinearity can be used for the purpose of damage detection. If no damage is present inside the specimen, i.e. the material can be assumed linear, the response of the structure at a higher excitation signal should be perfectly proportional (except from noise effects) to that obtained at the lowest excitation level. On the contrary, when the structure is damaged, the proportionality should no longer be valid due to the nonlinearities related to damage.

The SSM approach consists at first in exciting the damaged specimen with a sinusoidal signal at a comparatively low amplitude A_{low} and detecting its response v_{low} . The latter is thus linearly rescaled in amplitude to obtain the output signal v_{ref} that is expected to be the same as that of an intact specimen excited with a scaled amplitude $A_{\text{high}} = kA_{\text{low}}$ signal; k being the scale factor. The response of the structure v_{high} at an excitation amplitude equal to A_{high} is then acquired. The difference between the recorded signal v_{high} and the linearly rescaled signal v_{ref} is referred to as the scaled subtracted signal and can be expressed as

$$w(t) = v_{\text{high}}(t) - v_{\text{ref}}(t) = v_{\text{high}}(t) - kv_{\text{low}}(t) \quad (1)$$

If the structure is damaged, the subtracted signal $w(t)$ will contain the effects of the nonlinearities related to damage such as amplitude and phase variations at the fundamental frequency as well as at higher order harmonics. Conversely, the subtracted signal vanishes (except for noise effects) when the material is perfectly linear.

Two indicators may be adopted to assess the nonlinearity content, see also [3,4]. The first one refers to the maximum amplitude of the subtracted signal

$$\alpha = \max(w) + |\min(w)| \quad (2)$$

The second indicator is the root mean square of the subtracted signal

$$\beta = \left(\frac{1}{n} \sum_{i=1}^n w_i^2 \right)^{1/2} \quad (3)$$

Here n and w_i are the number of sampled points and the amplitude of the i th point of the subtracted signal, respectively. Once analysed in the time domain, the signals can be investigated in the frequency domain to put in evidence magnitude and phase differences between the linearly rescaled signal and the acquired one.

An application of the NWMS technique to the same specimen is also provided for comparison. This technique relies on the analysis of the modulation effect on a weaker high frequency probing wave by a stronger low frequency pumping wave that occurs in presence of structural nonlinearities. Exciting a damaged structure simultaneously with high and low frequency signals, the sideband components around the high frequency peak can be observed in the response signal as a result of the modulation effect. If the structure is intact this effect is less pronounced whilst it becomes more and more evident as damage increases. The frequencies at which the sidebands occur are

$$f_{s_n} = f_H \pm n f_L \quad (4)$$

where f_{s_n} is the frequency of the n th sideband, f_H is the frequency of the ultrasonic wave and f_L is the resonance low frequency. To quantify the extent of modulation it may be useful to refer to the following parameter

$$R = \frac{(A_1 + A_2)}{A_0} \quad (5)$$

relating the A_1 and A_2 of the first pair of sidebands to the amplitude A_0 of the high-frequency ultrasonic component.

3. Experimental Studies

This section presents the experimental procedure involved in the current investigations. The composite specimen together with the experimental equipment and the X-ray tests performed to assess the severity of damage are described in detail.

3.1. Composite specimen and experimental equipment

The specimen used in experimental tests was a rectangular 220×160 mm laminated composite plate with $[0_2/90_2]_s$ stacking sequence. The average laminate thickness was equal to 2 mm. The plate was cut from a panel made up from *Seal Texipreg® HSI60/REM* carbon epoxy prepreg layers and cured in autoclave at a maximum temperature of 160 °C and pressure of 6 Bar.

The plate was instrumented with four *PI Ceramic PIC 151* low-profile piezoceramic transducers (10 mm diameter, 0.25 mm thickness) and a *PI PL055.31, PICMA* piezoceramic stack actuator positioned as shown in figure 1 and 2. The stack actuator and three piezo transducers (A, B, C) were bonded on the same surface of the impact damage whilst the remaining transducer (D) was bonded in the opposite surface in correspondence with the transducers B. The transducers were surface bonded using a two-component epoxy adhesive and wired using additionally bonded connectors. The panel was freely suspended using thin nylon cords to minimize any nonlinearity associated with structural boundaries.

The excitation signals transmitted to the piezoceramic transducers were generated using a *TTI TGA5011A* function generator and amplified twenty times with a *FLC F20A* high voltage linear amplifier. The signals exciting the stack actuator were generated by a *TTI TG2000* function generator and amplified ten times with a *PI E-508 PICA* piezo amplifier. The main equipment used in the experimental investigation is shown in figure 3. A drop-weight impact testing machine with a 2.2 kg impactor was used in order to introduce damage onto the plate. The impactor was provided with a hemispherical indenter of 12.5 mm diameter and instrumented with a semiconductor strain-gauge bridge for dynamic load acquisition. An impact of 4.6 J energy was introduced at central position of the plate in order to obtain a delamination in the area of Barely Visible Impact Damage (BVID).

Non-destructive penetrant-enhanced X-ray inspections were carried out to identify and characterize internal damage. Radiographic analyses were done with a *HP Faxitron* cabinet. An X-ray picture of internal damage after the impact is shown in figure 4. Damage induced by the impact mainly consists of a delamination developing on the $90^\circ/0^\circ$ interface farthest from the impact side of the panel, together with a major matrix crack in the bottom 0° layers and shear matrix cracks in the 90° layers.

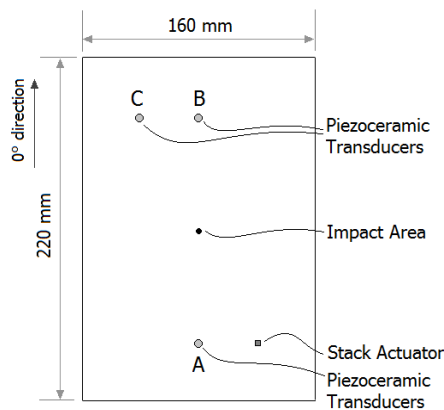


Figure 1. Representation of the composite plate.

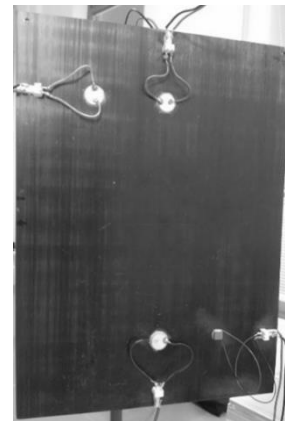


Figure 2. Experimental set-up for the composite plate.



Figure 3. Experimental equipment.

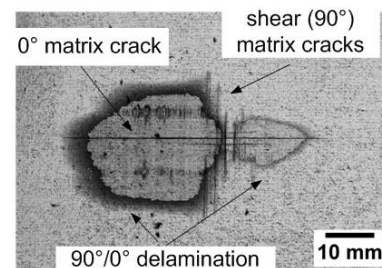


Figure 4. X-radiographs of impact damage.

3.2. Experimental procedure for damage detection – Scaling Subtraction Method

A modal analysis of the intact plate was firstly performed to find natural frequencies of the specimen. A sweep sine signal was used to excite the plate in the range between 10 and 60 kHz. Within this range, a resonant frequency of 10340 Hz was selected for further analyses as it had a clear frequency peak and good signal-to-noise ratio.

To perform the SSM test, the plate was firstly excited with a low amplitude (0.5 V peak-to-peak before amplification) sinusoidal wave applied to the piezoceramic transducer A. When stationary conditions were reached, the response signals were acquired from sensors B, C and D. A time window of 50 ms (517 cycles) and a sample frequency of about 10 MHz have been adopted in the test. The same procedure was then applied by varying the excitation amplitude between 1 and 8 V peak-to-peak (sixteen times the amplitude of the first excitation level) with a step of 1 V peak-to-peak. Each signal was

averaged 256 times in order to improve the signal-to-noise ratio. Excitation and acquisition signals were triggered and synchronized using the external trigger channel of the oscilloscope. The testing procedure was applied to the panel in both intact and damaged conditions.

Through a post-processing procedure, the offset of the signals was removed and the output signal related to the 0.5 V peak-to-peak excitation was rescaled in amplitude to be compared with those acquired at higher amplitudes (figure 5). The subtracted signals for each excitation level were calculated and analysed in time and frequency domain. The nonlinear indicators α and β , defined in equations (2) and (3), were then obtained and plotted against the excitation amplitude to assess nonlinear effects in the time domain. Once transformed in the frequency domain, the amplitude/phase differences at fundamental frequency between the linearly rescaled signals and the ones acquired at higher amplitudes were analysed and plotted against the excitation amplitude.

3.3. Experimental procedure for damage detection – Nonlinear Acoustic Wave Modulation

The same specimen was also analysed through the NWMS test, by simultaneously applying two excitation signals. The first one, excited by the *PI PL055.31* stack actuator, was a low-frequency sinusoidal wave at the resonant frequency of 410 Hz. The second signal, excited by a *PI Ceramic PIC 151* piezoceramic transducer, was a high-frequency ultrasonic wave. Two different resonant ultrasonic frequencies have been considered in the test, namely 28460 Hz and 45340 Hz. Transducers A, B and C were used in turn as actuators or sensors. The amplitude of the high-frequency signal was fixed at 2 V peak-to-peak (before-amplification) for both frequencies. Various amplitude levels of the low-frequency excitation were considered, ranging from 1 to 10 V peak-to-peak (before amplification). The test was performed in both intact and damaged conditions. The amplitude of the spectral sidebands was analysed by means of the R parameter defined in equation (5). The extent of modulation effects was investigated for different values of the high frequency excitation and for different configurations of excitations and sensing.

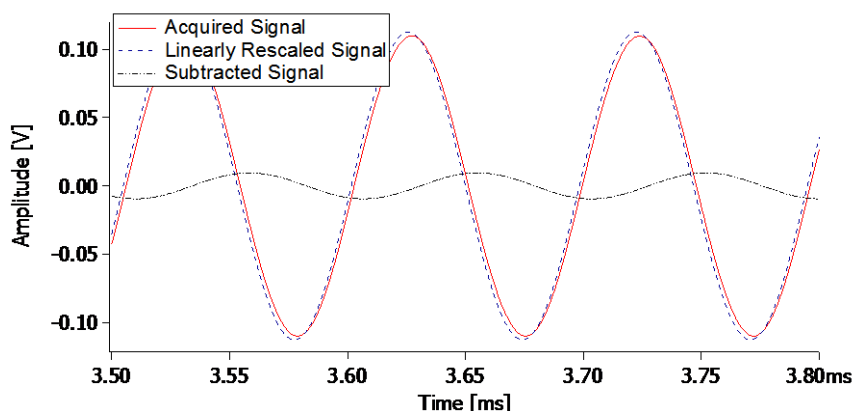


Figure 5. An instance of recorded signals.

4. Results and discussion

4.1. Scaling Subtraction Method

The nonlinear indicators α and β , are plotted in figures 6, 7 and 8 against the amplitude of the excitation signal (before amplification). Diagrams refer to the signals acquired from sensors B, C and D when the excitation is applied at sensor A. Both indicators α and β show that the difference between the linearly rescaled signals and the corresponding acquired ones increases as the input excitation increases. Although a nonlinear behaviour is detected also in the intact case, the extent of nonlinearities in the damaged case is found to be rather more marked.

To highlight the contribution to nonlinearities given by amplitude and phase variation, the recorded signals were analysed in the frequency domain. Figures 9 and 10 show the amplitude and phase

differences between undamaged and damaged cases. Relevant to the fundamental frequency, the difference in amplitude between the linearly rescaled signals and the recorded ones is plotted in figure 9a as a function of the amplitude of the input excitation (in this case the signals are recorded at sensor B). In the damaged case, the peak amplitude of the rescaled signal is slightly lower than that of the recorded signal (this leads to positive values of the difference between the two signals as shown in figure 9a). A similar behaviour is found in the intact case for lower excitation values whilst an opposite trend can be seen for higher values. Phase differences are plotted in figure 9b, showing that in the damaged case the rescaled signal always exhibits a phase delay with respect to the acquired one, which actually increases as the excitation amplitude increases. On the contrary, in the intact case the phase delay is very small, at least for low amplitude excitations. Figures 9 and 10 show that both amplitude and phase differences contribute to the damage indicators, even if a slightly larger influence of phase may be noted.

4.2. Nonlinear Wave Modulation Technique

Figure 11 gives an instance of the zoomed spectra obtained for the 45340 Hz ultrasonic excitation. The peak of the fundamental high-frequency signal and the first pair of sidebands are clearly visible in both undamaged and damaged conditions. The amplitude of these sidebands was analysed through the nonlinear parameter R . Some of the results obtained from the sideband analysis are provided in figure 12, where the parameter R is plotted against the low-frequency excitation level. In both damaged and undamaged cases the amplitude of the spectral sidebands increases with the low-frequency excitation amplitude. Generally, the values of R are higher in the damaged case and the differences between damaged and undamaged case become more and more evident as the low-frequency signal amplitude increases. The results show no significant difference between the two ultrasonic frequencies used. However, a more marked difference between damaged and undamaged cases was found when the high frequency excitation was transmitted from piezoceramic transducers located in B and C (that is, when high and low frequency excitations were in opposite positions with respect to the damage).

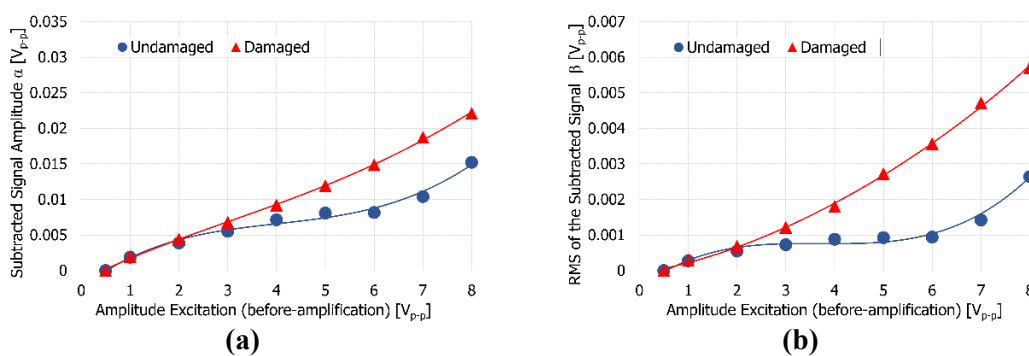


Figure 6. Nonlinear indicators α (a) and β (b) of the subtracted signal obtained for sensor B.

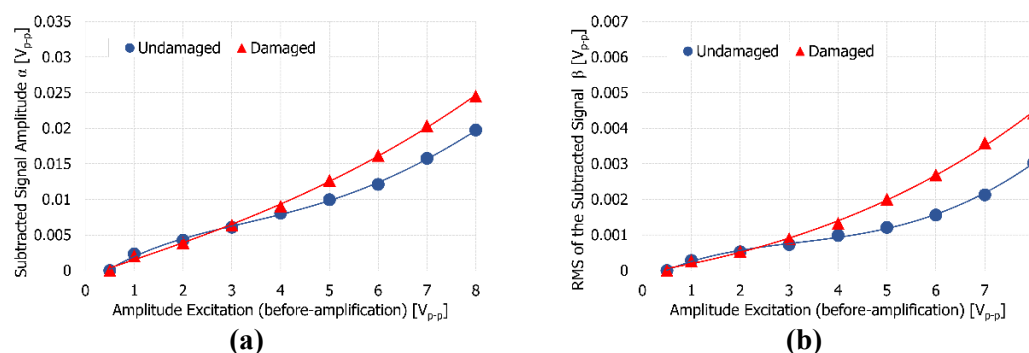


Figure 7. Nonlinear indicators α (a) and β (b) of the subtracted signal obtained for sensor C.

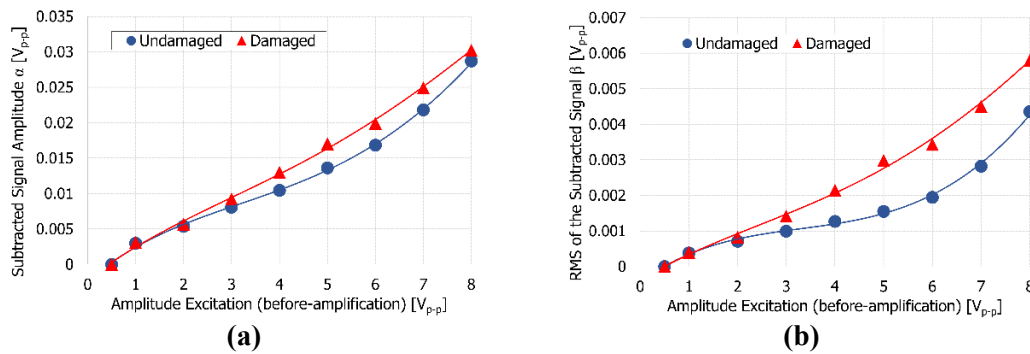


Figure 8. Nonlinear indicators α (a) and β (b) of the subtracted signal obtained for sensor D.

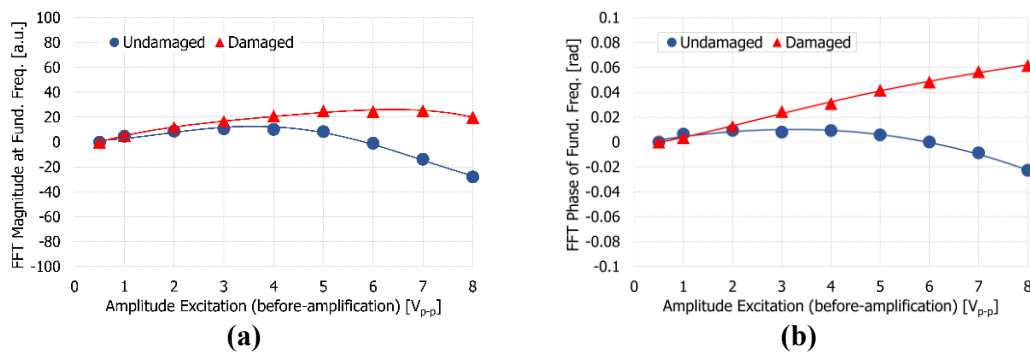


Figure 9. Amplitude (a) and phase (b) differences obtained in correspondence of the fundamental frequency peak.

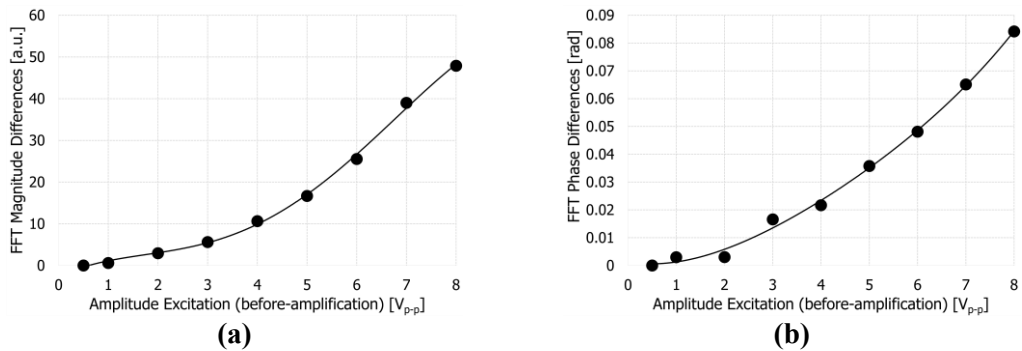


Figure 10. Amplitude (a) and phase (b) differences trend between intact and damaged cases.

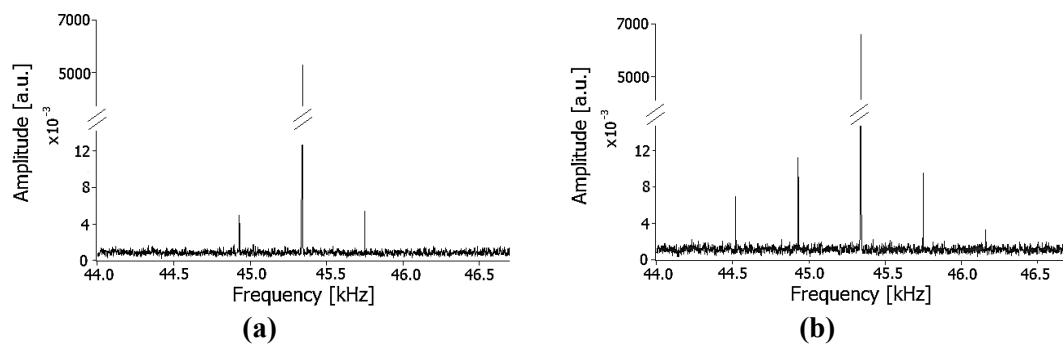


Figure 11. Examples of the power spectra for the undamaged (a) and damaged (b) cases.

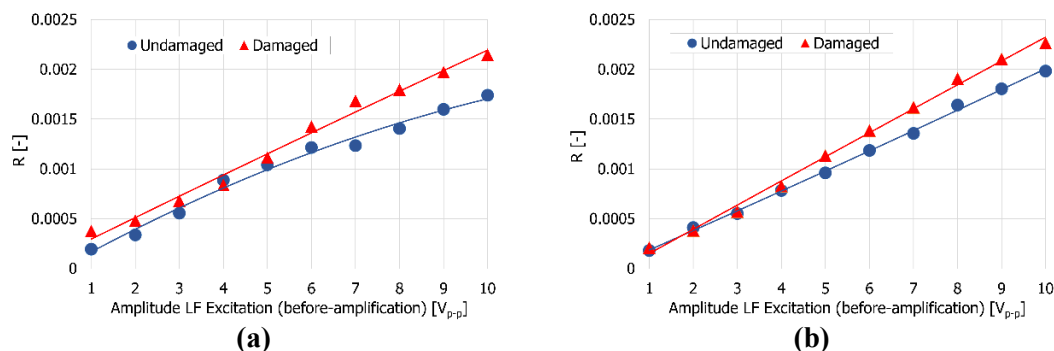


Figure 12. Intensity of modulation vs. low-frequency excitation level for 28460 Hz (a) and 45340 Hz (b) frequency excitations.

5. Conclusions

An application of Scaling Subtraction Method and Nonlinear Acoustic Wave Modulation techniques has been presented in the paper. The test specimen was a composite laminate plate with a barely visible impact damage. Surface-bonded piezoceramic transducers were used as actuators and as sensors. The response of the specimen has been analysed in time and frequency domain. Amplitude/phase nonlinearities and modulations effects have been analysed in order to discriminate between damaged and undamaged conditions. Although a nonlinear behaviour is detected also in the intact case, the extent of nonlinearities in the damaged case is found to be rather more evident for both the analysed techniques. When applied to composite specimens, the SSM may thus leads to a similar understanding of the nonlinear phenomena to those obtained for the NWMS technique. Further analyses are required to confirm these findings. Different kinds of composites and different damage severities should be investigated for monitoring the evolution of the nonlinear behaviour. Future works should also attempt to explain the obtained results with respect to the interaction mechanism between waves and damage.

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Acknowledgments

Andrea Frau gratefully acknowledges Sardinia Regional Government for the financial support of his PhD scholarship (P.O.R. Sardegna F.S.E. Operational Programme of the Autonomous Region of Sardinia, European Social Fund 2007-2013 - Axis IV Human Resources, Objective 1.3, Line of Activity 1.3.1.). The second author would like to acknowledge financial support from the Foundation for Polish Science (FNP) within the scope of the WELCOME Programme-project no. 2010-3/2.