Appl Compos Mater (2008) 15:115–126
DOI 10.1007/s10443-008-9061-7

Detecting Damage in Composite Material Using Nonlinear Elastic Wave Spectroscopy Methods

Michele Meo · Umberto Polimeno · Giuseppe Zumpano

Received: 23 July 2008 / Accepted: 25 July 2008 /
Published online: 10 September 2008
© Springer Science + Business Media B.V. 2008

Abstract Modern aerospace structures make increasing use of fibre reinforced plastic composites, due to their high specific mechanical properties. However, due to their brittleness, low velocity impact can cause delaminations beneath the surface, while the surface may appear to be undamaged upon visual inspection. Such damage is called barely visible impact damage (BVID). Such internal damages lead to significant reduction in local strengths and ultimately could lead to catastrophic failures. It is therefore important to detect and monitor damages in high loaded composite components to receive an early warning for a well timed maintenance of the aircraft. Non-linear ultrasonic spectroscopy methods are promising damage detection and material characterization tools. In this paper, two different non-linear elastic wave spectroscopy (NEWS) methods are presented: single mode nonlinear resonance ultrasound (NRUS) and nonlinear wave modulation technique (NWMS). The NEWS methods were applied to detect delamination damage due to low velocity impact (<12 J) on various composite plates. The results showed that the proposed methodology appear to be highly sensitive to the presence of damage with very promising future NDT and structural health monitoring applications.

Keywords Nonlinear elastic wave spectroscopy · Delamination · Damage detection

1 Introduction

The use of carbon fiber reinforced plastic (CFRP) composite materials has been increasing rapidly in wide range of industrial applications due to their excellent properties such as high stiffness to weight and strength to weight ratios, and fatigue properties.

M. Meo (✉) · U. Polimeno
Department of Mechanical Engineering, The University of Bath, Bath BA2 3LT, UK
e-mail: m.meo@bath.ac.uk

G. Zumpano
CUED, University of Cambridge, Trumpington Street, Cambridge CB2 1PZ, UK

The damages due to impact loads are one of the most critical points in the performance of composite laminated materials and the fragility of this class of material still limits their application especially in aerospace structures. In particular, impact can cause a significant amount of delamination, even though the only external indication of damage may be a very small surface indentation. However, the impacted surface exhibits only a barely visible blemish which easily escapes detection. This type of damage is often referred to as barely visible impact damage (BVID), and it can cause significant degradation of structural properties. If the damaged laminate is subjected to high compressive loading, buckling failure may occur.

In the past two decades, due to high cost of inspection of composite structures, when compared to metallic structures [3–5], the scientific community have been trying to develop reliable and effective non-destructive technique (NDT) to detect the occurrence of critical failure modes, such as delamination and debonding, and to estimate its position at the early stage so as to reduce the risk of further catastrophic failure.

A number of acoustic/ultrasonic damage detection techniques were developed to analyse the changes of linear properties due to the presence of damage. In particular, linear acoustic/ultrasonic methods study the changes of wave speed, waves reflection and refraction, and/or signal amplitude changes to assess the presence and location of structural anomalies. Yuan [6] adopted on-line acoustic–ultrasonic methods to study delamination damage in sandwich composites.

The use of guided waves in ultrasonic inspection of plate structures has been used successfully for the localization of defects (inclusions, delaminations, cracks) but is more complicated than conventional bulk wave inspection [7–10]. This is mainly due to dispersion effects and multimode propagation. Moreover, linear acoustics/ultrasonic methods can be difficult to apply to inhomogeneous materials, such as composite materials, and in particular to damaged materials where the crack size is comparable with the wavelength.

Therefore, there is the need to develop improved and more efficient means of detecting such damage. Detailed studies of dynamic non-linearities and hysteresis in inhomogeneous media have shown that the presence of rupture, cohesive bonds, opening/closing of microcracks, etc. in the material structure gives rise to strongly nonlinear dynamic phenomena accompanying the elastic wave propagation [1]. These non-linear effects are observed in the course of the degradation process much sooner than any degradation-induced variations of linear parameters (propagation velocity, attenuation, elastic moduli, rigidity, etc.). Non-linear parameters have proved to be very sensitive to the presence of any inhomogeneities and progressive degradation of the material structure [2].

Based on these studies a new class of promising NDE techniques, called non-linear elastic wave spectroscopy (NEWS) is being developed and it monitors the integrity of structures by analysing the material nonlinear elastic behaviour caused by the presence of damage [11–17]. Laboratory tests show that NEWS techniques appear to be more effective than linear acoustic methods since they are able to detect microcracks long before changes of linear acoustic properties [18].

2 Nonlinear Elastic Wave Spectroscopy (NEWS)

The NEWS techniques originally were developed to estimate the nonlinear elastic properties of heterogeneous material like rocks. It has been shown that some damaged materials have a complex compliance and have a nonlinear behavior that cannot be explained with classical nonlinear models [19]. The stress strain curve of damaged materials may exhibit classical nonlinearity, hysteresis, and discrete memory [19]. The stress–strain in one dimension in quasi static condition can be written as follow:

$$\sigma = \int K(\varepsilon, \dot{\varepsilon})\mathrm{d}\varepsilon \tag{1}$$

where σ is the stress, ε is the strain, $\dot{\varepsilon}$ is the time derivative strain and K is the elastic modulus. A phenomenological description of the non linear non classical hysteretic elastic modulus based on the Preisach–Mayergoyz space representation describing both second- and higher-order nonlinearity is shown in Eq. 2.

$$K(\varepsilon,\dot{\varepsilon}) = K_0\left\{1 - \beta\varepsilon - \delta\varepsilon^2 - \alpha[\Delta\varepsilon + \varepsilon(t)\mathrm{sign}\,(\dot{\varepsilon}) + \ldots]\right\} \tag{2}$$

where K_0 is the linear modulus, β and δ are second and third order nonlinearity, $\Delta\varepsilon$ is the local strain amplitude, α is a material hysteresis measure that takes into account also the history of stress through the terms sign $(\dot{\varepsilon})$, that equals +1 if the strain rate is positive and −1 if negative. Depending on the sign of β and δ and α the material may soften or harden when excited with increasing driving amplitude. Some material may exhibit a reduction/increase of the resonant frequency as a function of the driving amplitude.

Traditional acoustic/ultrasonic NDT try to detect variation of the linear Young Modulus K_0 caused by damage by analyzing wave speed changes, reflection of waves, linear attenuation, etc.). If damage increases the modulus K decreases. In contrast with linear methods, NEWS techniques are vibration/acoustic/ultrasonic NDT that try to detect the presence of anomalous behaviour (damage) by measuring the first, second order deviations of elastic modulus from the Hooke's law of elasticity.

Composite laminated materials are structural heterogeneous material exhibiting generally linear behaviour when undamaged, but when damaged under large strain amplitude may exhibit nonlinear hysteretical behaviour.

This paper presents a number of studies on various impact damaged composite material to highlight their nonclassical nonlinear behaviour and to demonstrate the capability of NEWS methods to detect the presence of damage and to assess its magnitude.

Two different NEWS methods are presented below: resonance (NRUS) and non-resonance based methods (NWMS).

2.1 Nonlinear Resonant Ultrasound Spectroscopy (NRUS)

In the case of hysteretical behaviour, if the material is excited with a sine wave with a certain amplitude A_1 (Fig. 1a), the stress strain curve describe a loop having an average modulus K_1 and the energy dissipated during the loading and loading is represented by shaded area of the smaller hysteresis loop of Fig. 1a. However, if we increase the amplitude A_2, the material will describe a different hysteresis loop with an average modulus K_2 and higher energy dissipated (area of the bigger hysteresis loop). This behaviour causes clearly modulus reduction and clearly an increase of the attenuation for larger amplitude excitation.

Therefore, this effect leads the way to use resonance methods where engineer can analyse the dependence of the resonance frequency on the strain amplitude while exciting the sample at relatively low amplitudes. The measurement of a frequency shift may reveal the presence of damage in the material. In Fig. 2 a schematic representation of the method is shown [19]; for undamaged material no frequency shift is present while in damaged material a frequency relative shift is manifest for increasing driving amplitudes. These methods are usually referred to as Nonlinear Resonance Ultrasound Spectroscopy (NRUS) [19].

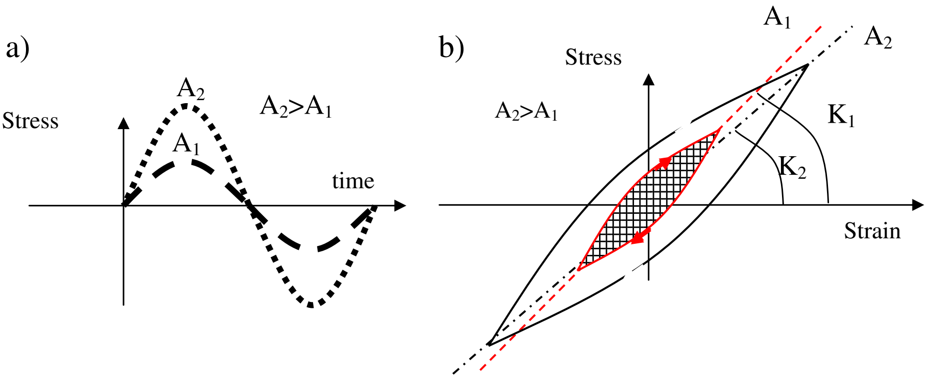


Fig. 1 **a** Excitation load $A_2 > A_1$. **b** Stress–strain curve for two different load amplitude

When exciting some damaged materials at large strain amplitude level, the nonlinear hysteretic parameter α is predominant [11] and it can be evaluated as follows:

$$\alpha \Delta \varepsilon = \frac{f_0 - f_i}{f_0} \tag{3}$$

where $\Delta\varepsilon$ is the average strain amplitude, f_0 is the natural frequency of intact material or the lowest resonance mode measured, f_i is the natural mode measured for each drive amplitude, represented by the maximum value of each curve shown in Fig. 2. The evaluation of relative frequency shift dependence (slope α) as function of the load (strain) amplitude can be used to provide an indication of damage presence and also of damage magnitude when a baseline of a previous material state is available.

Due to the presence of discontinuities in the stress–strain curve caused by sudden change from the loading to the unloading phase (cusps), the spectrum response can be characterized by the presence of odd harmonics of the fundamental excitations frequency (nf; n=1,3,5…; for example: $3f_1$, $5f_1 \ldots nf_1$ and $3f_2$, $5f_2 \ldots nf_2$).

2.2 Nonlinear Wave Modulation Spectroscopy (NWMS)

Matrix cracking, fiber debonding, delaminations, etc., may give rise to additional “nonclassical” nonlinearity wave effects generated by the material hysteretical behaviour.

Applying two continuous waves of with different frequencies, one high f_1 and one low f_2, in a damaged material, due to the vibration, the amplitude of the high-frequency wave will

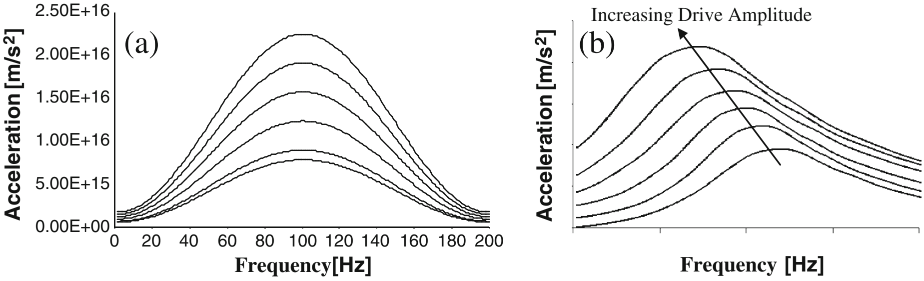


Fig. 2 Resonance frequency versus drive amplitude. **a** Intact sample, **b** damaged sample

be modulated with the low frequency. Correspondingly, in the frequency domain the wave spectrum acquires sidebands: new frequencies are created. This nonlinear process that is possible in undamaged materials (due to, e.g., Van der Waals forces in some materials) can be radically enhanced due to the presence of damage. If the nonlinearity is strong enough, additional sidebands can appear, thus forming a complex modulational spectrum (Fig. 3).

As shown in [11–19], in the presence of cracks, defects, etc. composite material can start to behave in a hysteretic fashion, and sidebands and harmonics of the excited frequencies are generated. Damage acts as a multiplier and nonlinear mixer of the excitation frequencies. In particular, for purely hysteretical damaged material, only odd harmonics [11] are present (no even harmonics) and they follow a quadratic behaviour with the fundamental strain amplitude. Moreover, an intermodulation experiment using frequencies f_1 and f_2 with amplitudes A_1 and A_2 would generate second-order sideband f_2+2f_1 with amplitudes proportional to $\alpha A_1 A_2$. This is schematically represented in Fig. 4.

2.3 Damage Detection

In this section, the capability of the presented NEWS methods to detect the occurrence of damage is reported. In particular, it is worth mentioning that the tests were performed on composite plate whose mechanical properties and layout were unknown. This was intentional in order to assess the capability of the NEWS methods to be used without an a priori knowledge of the material state and properties.

2.3.1 Nonlinear Resonant Ultrasound Spectroscopy (NRUS)

Single-mode nonlinear resonance vibration acoustic spectroscopy tests were conducted on a number of T300/5208 Carbon/Epoxy unidirectional composite plates (170×110×4 mm). The specimens were damaged by a low velocity impact (7 J). The damage introduced was a barely visible impact damage characterised by a small indentation on the front face, and by the back-plate delamination (Fig. 5).

The plates were excited at its first bending natural frequency through a speaker with constant amplitude. The experiments were performed using different drive amplitudes, in order to measure the resonance shift as a function of external amplitude. The results showed that (Fig. 6) as the excitation level increased, the elastic nonlinearity would manifest itself as a shift in the resonance frequency. The pristine sample did not show any frequency shift

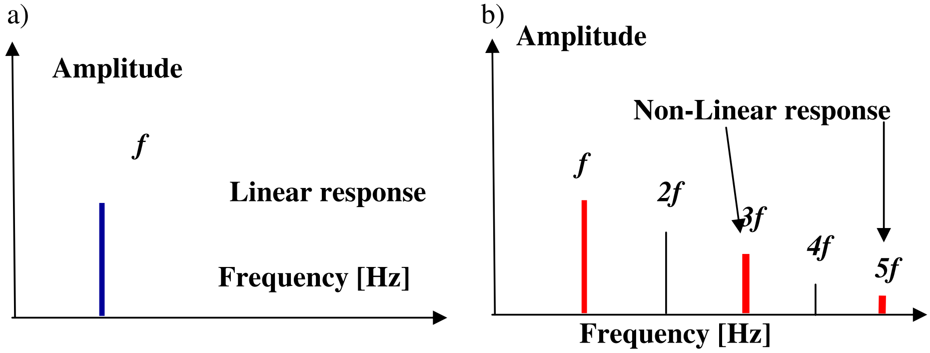


Fig. 3 **a** Spectrum response of linear material. **b** Spectrum response of hysteretic material

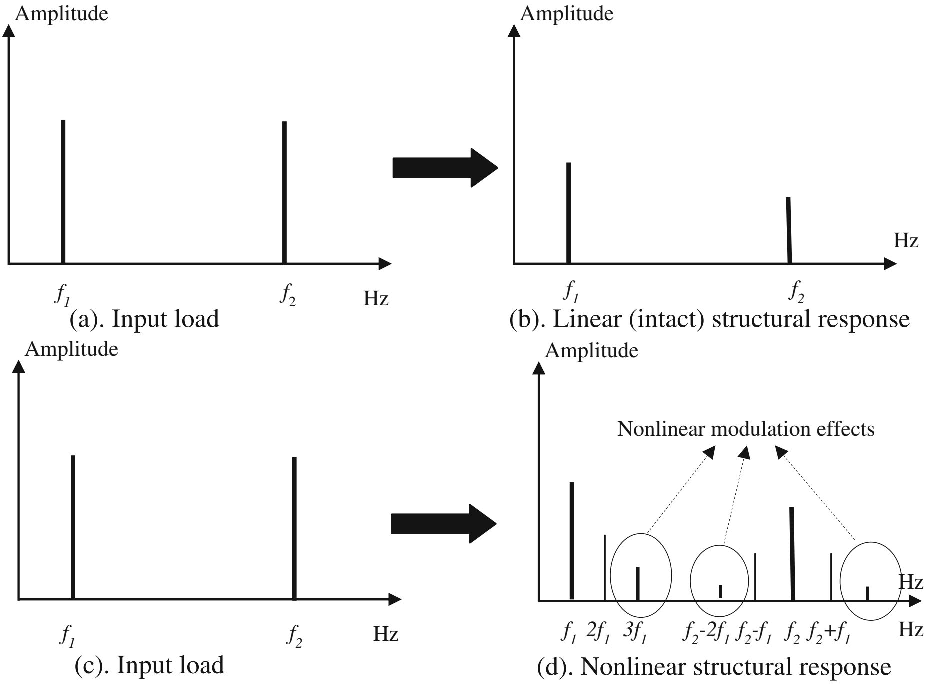


Fig. 4 Linear and non linear modulation effect. **a** Excitation frequencies. **b** Response of a linear undamaged. **c** Excitation frequencies. **d** Nonlinear response of an hysteretic damaged material: harmonics (nf_1; n= 1,3,5…) and sidebands ($f_2 \pm nf_1$; n=2,4,…)

as a function of the driving amplitude. As the damage was introduced, the NRUS test revealed a corresponding increase in the nonlinear response. The measured change in nonlinear response was much more sensitive than the change in linear modulus. In particular, no change of the linear modulus was observed. In this particular case, the frequency shift is a manifestation of nonlinearity due to the presence of the matrix cracks, fiber breakage and back-plate delamination.

2.3.2 Nonlinear Wave Modulation Spectroscopy (NWMS)

NWMS tests were performed in order to assess if this NEWS method could also assess the presence of impact damage in two different plates (AS4/3502). Both undamaged and

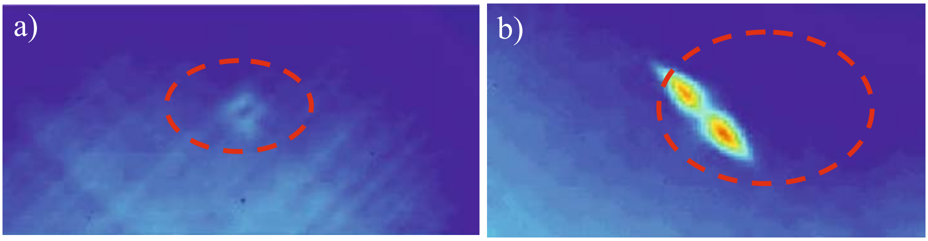


Fig. 5 Thermography images—**a** front face, **b** back-plate

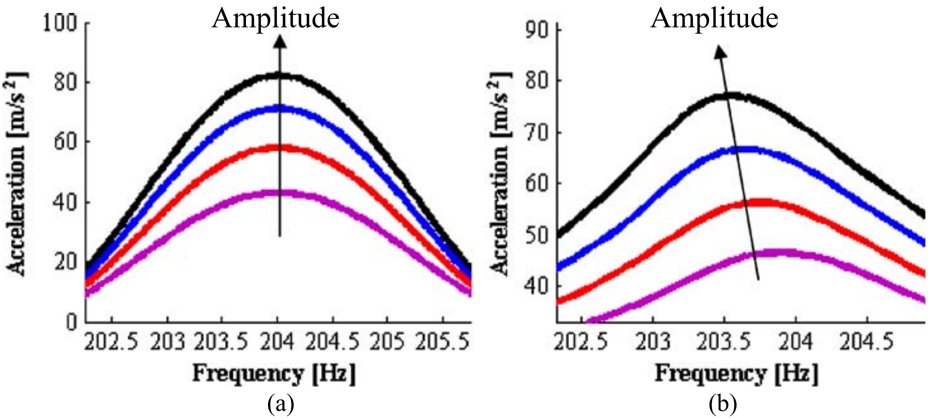


Fig. 6 Resonance curve: **a** undamaged sample, **b** damaged sample

damaged plate was investigated. The fundamental frequencies (f_1 and f_2) used were the first and the third resonance modes of the sample ($199<f_1<201$ Hz, $2{,}230<f_2<2{,}260$ Hz) with different external load amplitudes. The undamaged plate was tested with different driving amplitude, and in the output spectrum no harmonics or sidebands were observed (Fig. 7a): this showed that no interaction between the low and high frequency component was generated indicating the absence of microdamage (cracks).

After the impact was introduced in the composite plate, harmonics and sidebands were generated (Fig. 7b). We can observe that the amplitude of the sidebands and harmonics increase with the increase of the amplitude of the f_1. The results clearly show that the impact damage introduced material nonclassical nonlinear hysteretical behaviour, in addition to the linear effects as shown in Fig. 7b. The presence of the harmonics and sidebands were a clear indication of fiber breakage, matrix cracking and delamination.

2.4 Damage Magnitude

In this section, the capability of the presented NEWS methods to detect the magnitude is reported.

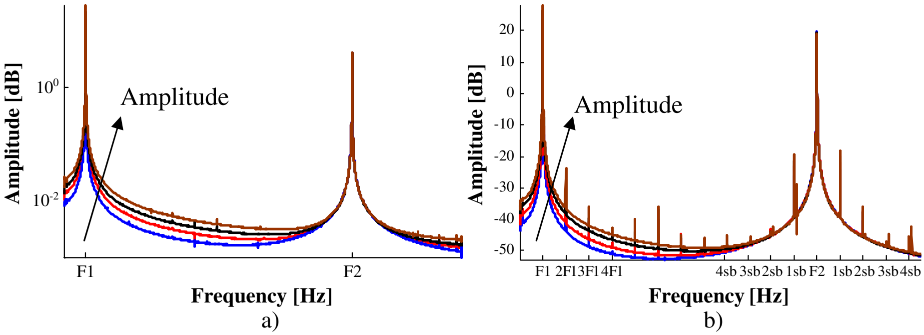


Fig. 7 Fast Fourier transform: **a** undamaged sample, **b** damaged sample

Table 1 Impact tests

Specimen	Thickness (mm)	Impactor (mm)	Energy (J)	Mass (kg)	Dent (mm)	C-scan area (cm^2)
1	4	16	10.24	6.22	0.12	3.90
2	4	6	9.85	6.24	0.22	2.90
3	4	20	10.34	6.24	0.12	3.60

2.4.1 Nonlinear Resonant Ultrasound Spectroscopy

In order to understand if NEWS methods could also provide information on the damage magnitude, three different carbon epoxy composite plates with different damage size were investigated. The samples were impact damaged. Details of the impacting energy and resulting damage are shown in Table 1. Different energy levels were used and the delamination area was measured using a C-scan. NRUS tests were conducted by using the same natural frequencies (first resonant mode) and boundary conditions for the three different samples.

Mechanical properties of the sample and the extent of the damage were unknown when performing the tests. A measure of the damage was evaluated by measuring the nonlinear parameter α. The results of the NRUS test are shown in Fig. 8a–c. The three samples showed a significant shift of resonance frequency with an increase of the external drive amplitude.

An indication of the damage magnitude was obtained by plotting the nonlinear parameter α against the delamination area as shown in Fig. 9. The result clearly shows that the behaviour of non linear parameter was strongly dependent on the damage severity, i.e.

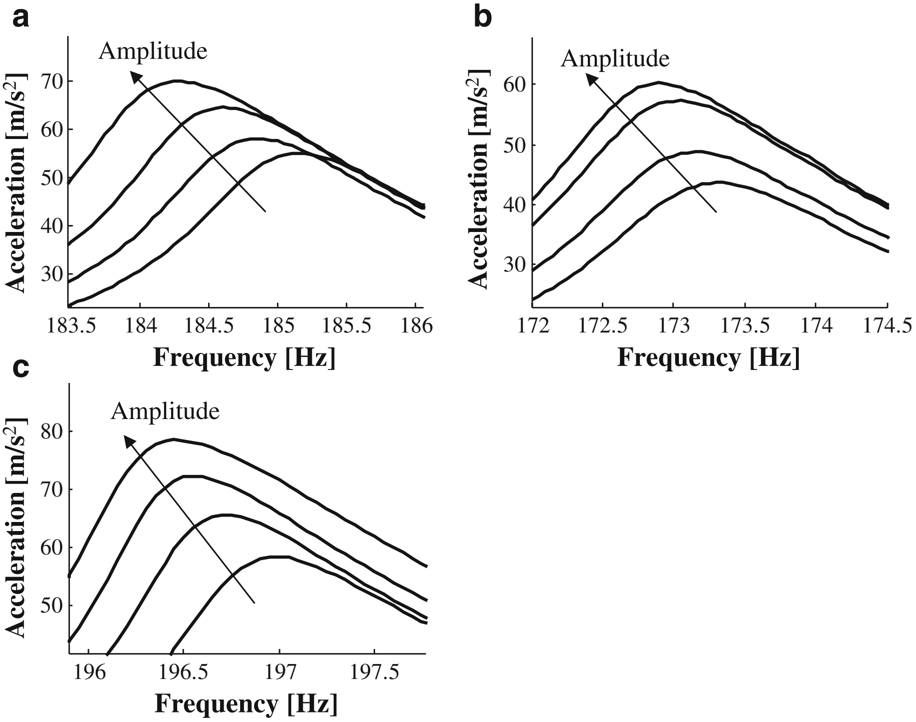


Fig. 8 NRUS tests: **a** sample 1, **b** sample 2, **c** sample 2

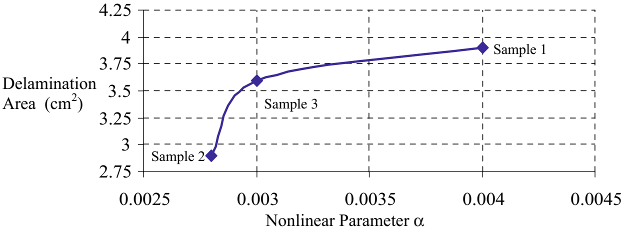


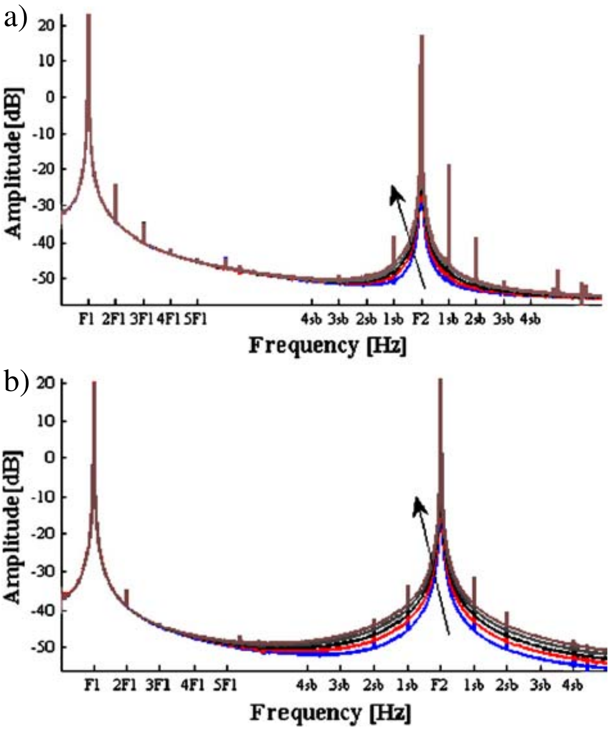
Fig. 9 Delamination area vs. non linear parameter α

the higher the nonlinear parameter the higher the delamination area. The results showed that the nonlinear parameter is highly sensitive to the damage magnitude and it could be used to assess progressive fatigue damage or cyclic compression damage after a low velocity impact. While for composite materials in pristine condition the nonlinear parameter was zero, to assess the magnitude of the damage (delamination area, matrix cracking, etc.) a material reference state of the composite material is needed.

2.4.2 Nonlinear Wave Modulation Spectroscopy

Similarly, Nonlinear Wave Modulation method was analysed to understand if it could provide information on the damage magnitude (sample specified in Section 2.3.2). The spectrum of the two different samples damaged with different impact energy level (9 and 10 J) was compared as shown in Fig. 10.

Fig. 10 Harmonics and sidebands generation at low and high frequency excitation: **a** sample 1—impact energy 9 J, **b** sample 2—impact energy 10 J



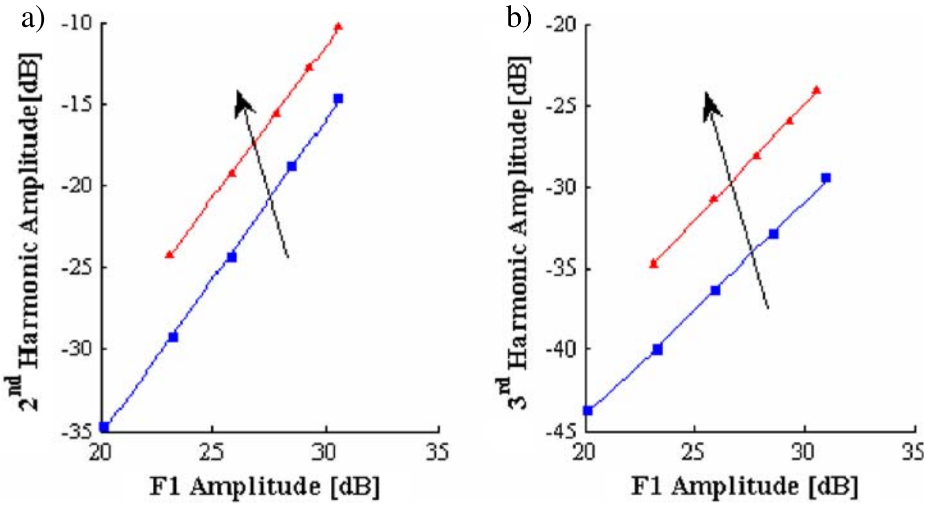


Fig. 11 Damaged samples: **a** second harmonics vs amplitude of f_1, **b** second harmonics vs amplitude of f_1. The marker (■) indicates the sample 1 with smaller delamination area

In order to highlight the influence of the damage magnitude on the material nonlinear elastic behaviour, a comparison of second and third harmonics of the driving frequency as a function of the fundamental amplitude f_1 was made for two composite plates as shown in Fig. 11. The result show that the harmonics amplitudes level, as a manifestation of nonlinearity, is strictly dependent on the damage (delamination) size.

Similar behaviour was observed for the sidebands of the high frequency (f_2). In Fig. 12, the first two right sidebands are displayed against the f_2. The magnitude of the sidebands is clearly dependent on the damage severity (delamination area), and likewise the low frequency response harmonics, the increase of damage size cause an increase of the amplitude of the sidebands.

These results show that also the amplitude of the harmonics and/or sidebands can be used to assess the magnitude of damage or the magnitude of the hysteretical nonlinear effects.

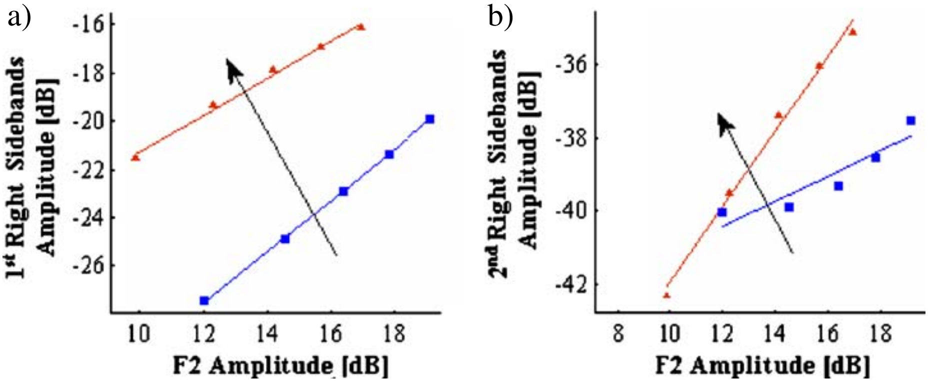


Fig. 12 Right sidebands for both samples. **a** First sideband: (F_2+F_1), **b** the second sideband is displayed (F_2+2F_1). The marker (■) indicates the sample 1 with bigger delamination area

It is, however, worth mentioning that also for this damage parameter, a baseline or a reference state of the composite material is needed to assess the integrity of the structures.

3 Conclusions

This paper presented a series of damage detection investigation carried out using Nonlinear Elastic Wave Spectroscopy (NEWS) methods.

Two methods were presented: NRUS and NWMS. The NRUS method is based on observation of resonance shit frequency caused by an increment of driving amplitude. The NWMS method monitors the generation of harmonics and sidebands on the spectrum of acquired signal excited by a bi-tone signal (NWMS).

NRUS and NWMS tests were performed on various composite materials. The harmonic, sideband amplitudes and α parameter highlighted behaviour compatible with the theory and previous experimental test found in literature [1–2, 11–19].

The overall results showed that NEWS methods can detect the presence of damages on composite structure, even when this is contained in a small area. This particular useful when trying to detect hardly visible due low velocity impact damage.

The measured nonlinear effects, like nonlinear parameter α, harmonics and sidebands amplitude, are strongly dependent on the damage entity showing that the NEWS methods are not only capable to detect the presence of damage, but also the damage severity. However, further studies are required to link the magnitude of nonlinear parameters with the entity of damage.

References

1. Johnson, P.: The new wave in acoustic testing. Mater. World **7**(9), 544–546 (1999)
2. Meo, M., Zumpano, G.: Nonlinear elastic wave spectroscopy identification of impact damage on a sandwich plate. Compos. Struct **71**(3–4), 469–474 (2005)
3. Bar-Cohen, Y.: In-service NDE of aerospace structures—emerging technologies and challenges at the end of the 2nd millennium. NDT.net **4**(9), 1–21 (1999)
4. Tan, K.S., Guo, N., Wong, B.S., Tui, C.G.: Experimental evaluation of delaminations in composite plates by the use of Lamb waves. Compos. Sci. Technol **53**, 77–84 (1995). doi:10.1016/0266-3538(94)00076-X
5. Lemistre, M., Guoyon, R., Kaczmarek, H., Balageas, D.: Damage localization in composite plates using wavelet transform processing on Lamb wave signals. In: Chang, F.-K. (ed.) Structural Health Monitoring, pp. 861–870. Technomic, Lancaster (1999)
6. Yuan, S., Zhu, X., Tao, B., Wang, L.: Application of stress wave factor technology to damage monitoring of sandwich structure. Journal of Data Acquisition & Processing **15**, 486–490 (2004)
7. Rosalie, S.C., Vaughan, M., Bremmer, A., Chiu, W.K.: Variation in the group velocity of Lamb waves as a tool for the detection of delamination in GLARE aluminium plate-like structures. Compos. Struct **66**, 77–86 (2004). doi:10.1016/j.compstruct.2004.04.024
8. Diamanti, K., et al.: Lamb waves for the non-destructive inspection of monolithic and sandwich composite beams. Compos. Part A. Appl. Sci. Manuf **36**(2), 189–195 (2005)
9. Diamanti, K., et al.: Non-destructive inspection of sandwich and repaired composite laminated structures. Compos. Sci. Technol **65**(13), 2059–2067 (2005). doi:10.1016/j.compscitech.2005.04.010
10. Kessler, S.S., et al.: Damage detection in composite materials using Lamb wave methods. Smart Mater. Struct **11**(2), 269–278 (2002). doi:10.1088/0964-1726/11/2/310
11. Van Den Abeele, K., Johnson, P.A., Sutin, A.: Nonlinear elastic wave spectroscopy (NEWS) techniques to discern material damage, part I: nonlinear wave modulation spectroscopy (NWMS). Res. Nondestruct. Eval **12**(1), 17–30 (2000). doi:10.1080/09349840008968159
12. Guyer, R.A., Johnson, P.A.: Nonlinear mesoscopic elasticity: evidence for a new class of materials. Phys. Today. (April):30–36 (1999). doi:10.1063/1.882648

13. Van Den Abeele, K., De Visscher, J.: Damage assessment in reinforced concrete using spectral and temporal nonlinear vibration techniques. Cem. Concr. Res **30**(9), 1453–1464 (2000). doi:10.1016/S0008-8846(00)00329-X
14. Campos-Pozuelo, C., Gallego-Juárez, J. A.: Experimental analysis of the nonlinear behaviour of fatigued metallic samples. In: WCU 2003, Paris, 7–10 September (2003)
15. Van Den Abeele, K.E.-A., Sutin, A., Carmeliet, J., Johnson, P.A.: Micro-damage diagnostics using Nonlinear Elastic Wave Spectroscopy (NEWS). NDT Int **34**, 239–248 (2001). doi:10.1016/S0963-8695(00)00064-5
16. Van Den Abeele, K., Van de Velde, K., Carmeliet, J.: Inferring the degradation of pultruded composites from dynamic nonlinear resonance measurements. Polym. Compos **22**(4), 555–567 (2001). doi:10.1002/pc.10559
17. Meo, M., Zumpano, G.: Impact damage identification on sandwich plates through nonlinear elastic wave spectroscopy. In: 5th International Conference on Composite Science and Technology (ICCST/5), Sharjah, UAE, 1–3 (2005)
18. Nagy, P.B.: Fatigue damage assessment by nonlinear ultrasonic material characterization. Ultrasonics **36** (1–5), 375–381 (1998)
19. Ostrovsky, L.A., Johnson, P.A.: Dynamic nonlinear elasticity in geomaterials. Riv. Nuovo Cim **24**(7), 1–46 (2001)