NONLINEAR VIBRO-ACOUSTIC WAVE MODULATIONS FOR IMPACT DAMAGE DETECTION IN COMPOSITES

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Abstract

The paper presents a case study of impact damage detection in composite structures. Two composite plates were used in these investigations. One plate was impacted with known energy levels whereas the other plate was left intact. Ultrasonic C-scanning was used to reveal delaminations in the impacted plates. The plates were instrumented with surface-bonded, low-profile piezoceramic transducers that were used for ultrasonic excitation. A low-frequency excitation was used in order to vibrate the plate modally. At the same time a high-frequency ultrasonic wave was introduced to the plate. Ultrasonic responses were used to detect impact damage. Analysed power spectra revealed a pattern of sidebands around the main ultrasonic component for the plate with delaminations.

1 Introduction

Composite materials have been widely used in many advanced engineering structures due to high specific strength, light weight, resistance to fatigue/corrosion and flexibility in design. Applications examples of composite materials can be found in many industries including transportation. Composites are particularly attractive in aerospace structures. Despite of all these benefits the susceptibility of composite materials to incur impact damage is well known and creates a major concern related to integrity in many structures. In aerospace low velocity impacts are often caused by bird strikes, tool drops during manufacturing and servicing or runway stones during take-off. Such impacts may result in various forms of damage such as indentation, delamination, or fibre/matrix cracking, leading to severe reduction in strength and integrity of composite structures. Although structures designed with safe-life principles can withstand in theory catastrophic failures, impact damage detection is an important problem in maintenance of aircraft and space structures. Visible damage can be easily detected and remedial action taken to maintain structural integrity. However, a major concern to end-users is the growth of undetected, hidden damage caused by low velocity impacts and fatigue. This undetected, hidden damage is also known in aerospace applications as Barely Visible Impact Damage (BVID). Failure to detect BVIDs may result in a catastrophe.

Various methods have been developed for impact damage detection in composite structures over the last few decades. This includes different Non-Destructive Testing (NDT) techniques based on visual inspection, ultrasonic testing, acoustic emission, vibrothermography or X-rays [1-2] Although major effort has been put to automate inspection (e.g. robot-assisted scanning systems), current NDT techniques used for damage detection are labour-intensive, timeconsuming and often expensive. Structural Health Monitoring (SHM), which comprises sensors integrated with structures to assess structural health, can offer a solution to this problem. Recent years have shown a range of different SHM techniques developed for damage detection in composite structures. Guided ultrasonic waves [3-4] and nonlinear acoustic [5-6] techniques are particularly attractive due to their ability of inspecting large structures with a small number of transducers. Nonlinear vibration and nonlinear acoustic effects have been also used for damage detection for many years [7-10]. Application examples include methods based on: second harmonic frequency generation, quasi-static time-of-flight measurements, frequency mixing, resonance spectra, reverberation analysis, modulation analysis and investigations of slow dynamic behaviour. The majority of these investigations are related to fatigue crack detection in metallic structures. Applications to composite structures are still limited and include second harmonic imaging technique [11], nonlinear slow dynamics [12], sidebands analysis [9] or cross-modulation techniques [13].

2 Nonlinear acoustics

One of the non-destructive methods of damage detection is non-linear acoustics. The major paradigm of the method is based on observation and analysis of various nonlinear acoustics phenomena manifested by structural signal responses [14-17]. It is generally acknowledged that damage detection sensitivity of nonlinear acoustics is much higher than that of classical linear methods. This allows one to detect defects in structures at the very early stage. Nevertheless nonlinear acoustics methods also have some limitations. One of the major limitations comes from the variety of different nonlinear effects arising from nonlinear acoustics tests [17-18]. It is often very difficult – if not impossible - to separate nonlinear effect related to damage from non-damage-related nonlinearity sources like boundary conditions, structural contacts, joints, inherent material nonlinearities or instrumentation measurement chain [19]. Some of these nonlinear effects are not yet fully understood and interpretation of experimental results is often difficult. Another problem associated with nonlinear acoustic application relates to experimental set-up and procedure. Various methods of excitation of monitored structures - such as speakers [20-21], shakers [17,22], hammers [23], lasers [24-25] and piezoceramics transducers [25-26] - can be found in the literature. Also different types of signal acquisition techniques were carefully investigated [27-28]. Nevertheless many important questions still arise.

In contrast to the classical ultrasonic methods, nonlinear acoustics uses different phenomena to assess condition of the structure. There are many different methods of nonlinear acoustics. One of the most widely used is the analysis of super- and sub- harmonics generated as a result of contact acoustics nonlinearity [29]. Another techniques based on theory of stiffness asymmetry and non-linear relationship between strain and stress (i.e. nonlinear elasticity) [29]. Various techniques based on this theory have been developed to detect material imperfections. Different approaches consider local phenomenon that arises as result of interaction of acoustic waves with contact-type interfaces [30-31]. Numerous inspection techniques based on generation of higher-harmonics, frequency mixing, analysis of slow dynamics, reverberation analysis and signal modulations have been developed over the last twenty years.

The method presented in this paper utilises the combined vibro-acoustic modulation interaction of high-frequency ultrasonic wave and low-frequency vibration (modal) excitation. This two excitations are introduce to the structure simultaneously (Figure. 1a). When the monitored structure is intact or undamaged, the spectrum of the signal response exhibits only the two major frequency components corresponding the propagating ultrasonic wave and low frequency excitation (Figure 1b). When the monitored structure is damaged, the spectrum of the response signal contains additionally sidebands around the main ultrasonic component (Figure 1c).

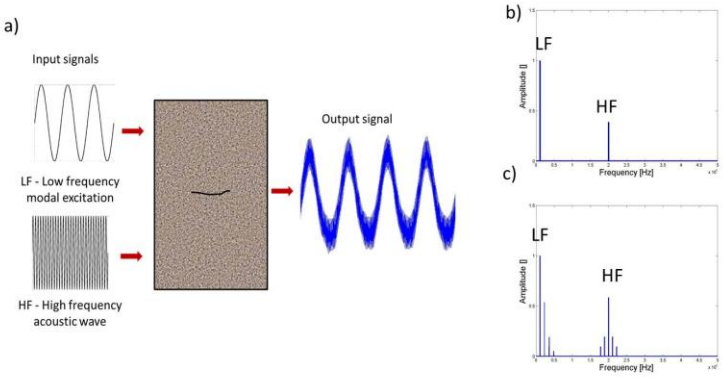

Figure 1. The principle of vibro–acoustic modulation: (a) schematic diagram illustrating the method; (b) power spectrum of response signal for undamaged structure; (c) power spectrum of response signal for damaged structure.

The number of sidebands and their amplitude depends on intensity of modulation and strongly relates to damage severity. The frequencies of these sidebands are equal to

$$f_{s_n} = f_H \pm n f_L \tag{1}$$

where f_{Sn} is the frequency of the n-th (n¬ =1, 2, 3, …, n) sideband, f_H is the frequency of acoustic wave and f_L is the frequency of modal excitation. The intensity of modulation is described by the R parameter, estimated from the amplitudes of two major sidebands A_1 and A_2 and the high-frequency component A_0

$$R = \frac{(A_1 + A_2)}{A_0} \tag{2}$$

3 Impact test

This section describes composite specimens used and impact tests undertaken to introduce damage to these specimens. The composite plate was manufactured from carbon/epoxy (Seal HS160/REM) unidirectional prepreg layers. The stacking sequence of the laminate was [03/903]s . The average laminate thickness was equal to 2 mm. The plates were cured in an autoclave at a maximum temperature of 160°C and a maximum pressure of 6 bar. The in-plane stiffness properties of the unidirectional prepreg layers (as obtained by tests on 0° and [+45/-45]2s coupons) are given in Table 1.

E_x = 93.7 GPa	E_y = 7.45 GPa	G_{xy} = 3.97 GPa	ν_{xy} =0.261

Table 1. In-plane stiffness properties of the investigated composite plates.

The specimen was ultrasonically C-scanned prior to testing to assess the quality of the laminate and to exclude any presence of possible manufacturing defects. Impact tests were conducted using an instrumented drop-weight testing machine. The composite panel was simply supported by a steel plate having a rectangular opening of 45 mm x 67.5 mm in size (with the longer side along the 0° direction) and impacted at the centre of the opening. The impactor of the drop-weight machine had a mass of 2.3 kg and was equipped with a hemispherical indenter of 12.5 mm in diameter. The 3.9 J impact energy were obtained by selecting the appropriate drop height of the impactor. The absorbed energy was evaluated by measuring (by an infra-red sensor) the velocities of the impactor immediately before and after the impact; the contact force was measured by means of a semiconductor strain-gage bridge bonded to the indenter. The impact force characteristics are presented in Figure 2. C-scan was used to characterize nature and extent of internal damage, as illustrated in Figure 3. The calculated area of damage was established as 326mm^2.

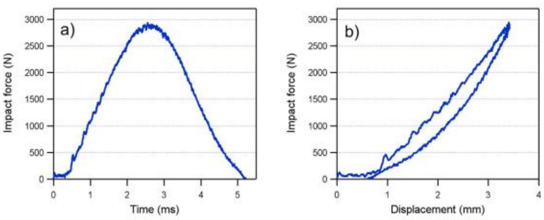

Figure 2. Impact force: a) vs. time, b) vs. displacement.

Figure 3. Image of delaminated area: a) X-ray based, b) C-scan based.

3 Nonlinear acoustics test – experimental arrangement.

This section describes tests performed for damaged and intact composite specimens. The experimental work included modal testing, and nonlinear acoustics tests. The following parameters were determined during experimental works: modulation intensity and first order sidebands amplitudes for two selected modes.

1.1 Modal analysis

An experimental modal test was performed in order to obtain modal frequencies of the composite specimen. The plate was freely suspended using elastic cords to avoid nonlinearities from boundaries and modally excited using a surface-bonded *NOLIAC* CMAP4 stack actuator. A white noise signal was used to excite the structure. The excitation signal was generated by a built-in *Polytec* signal generator and amplified by an *EC Electronics* amplifier. A *Polytec* PSV laser was used for non-contact measurements of ultrasonic responses. The Frequency Response Functions (FRFs) were calculated from the experimental input and output data using the *Polytec* software. An example of the FRF amplitude is presented in Figure 4 where a number of vibration modes of the specimen can be observed. FRF amplitudes were gathered from the 17 x 27 measurement grid to obtain the relevant mode shapes corresponding to the selected natural frequencies. Figure 5 shows examples of the two mode shapes selected to further analyses. The resonance frequencies of the 2nd (174 Hz) and 7th (459 Hz) vibration modes were selected for the low-frequency excitation in nonlinear acoustic tests.

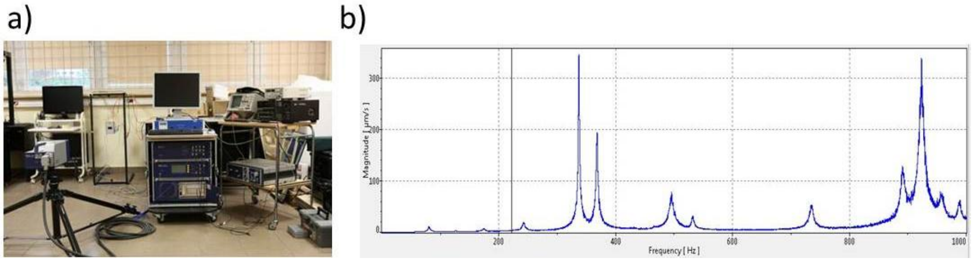

Figure 4. :a) . Experimental arrangements for modal analysis test, b) Amplitude of the Frequency Response Function for the composite specimen.

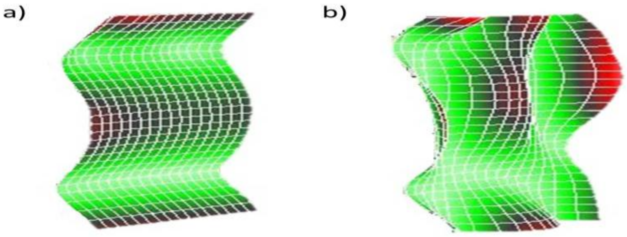

Figure 5. The first two mode shapes - 2nd mode – 174 Hz (b); 7th mode - 459 Hz.

1.2 Nonlinear acoustics – experimental set-up and procedure

Nonlinear acoustics tests were performed for both the undamaged and damaged specimens after damaging the laminate with an 3,9 J low velocity impact. The piezoceramic transducers was attached to the plate using two component epoxy adhesive. An ultrasonic sine wave (HF = 60 kHz; peak-to-peak amplitude = 60 V) was introduced to the low-profile piezoceramic transducer. At the same time, the structure was vibrated using the piezoceramic stack actuator driven by a sinusoidal (LF equal to 174 Hz for the second mode and 459 Hz for the seventh mode) excitation with amplitudes equal to 160 V pp and 120Vpp respectively . The response signal was measured by the PSV *Polytec* scanning laser vibrometer. Figure 6 illustrates the experimental arrangement used for nonlinear acoustics tests.

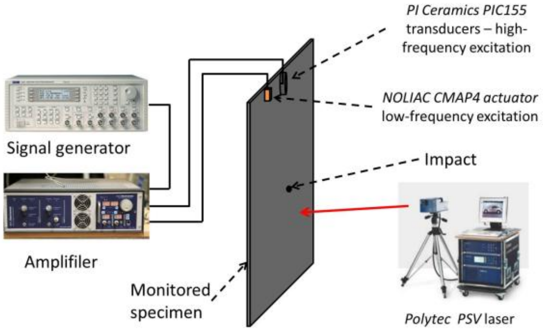

Figure 6. Experimental set-up used for the nonlinear vibro-acoustic tests.

4 Results and discussion

The power spectra were calculated from the acoustic response signals. The spectra were zoomed around the fundamental harmonic of the 60 kHz acoustic wave in order to reveal possible modulation sidebands. Figure 7 shows examples of power spectra from acoustical responses for the undamaged (Figure 7a) and damaged (Figure 7b) plate. A series of modulation sidebands – corresponding to the frequency of the vibration/modal excitation – around the fundamental 60 kHz ultrasonic component can be clearly observed when the plate is damaged. Some other components can also be observed in the spectra. However these components do not correspond to any modal frequencies of the monitored specimen and therefore are difficult to explain.

Modulation intensity was analysed using amplitudes of the carrier frequency and the first modulation sidebands, as described above. The resulting *R* parameter was calculated for damaged and undamaged plates. The results are presented in Figure 8. Although, the intensity of modulation was smaller for low amplitude level of modal excitation, a significant increased of *R* parameter can be observed for the damaged plate after the level of excitation exceeded 60 V . This suggests that damage severity assessment is possible when nonlinear acoustic tests are performed.

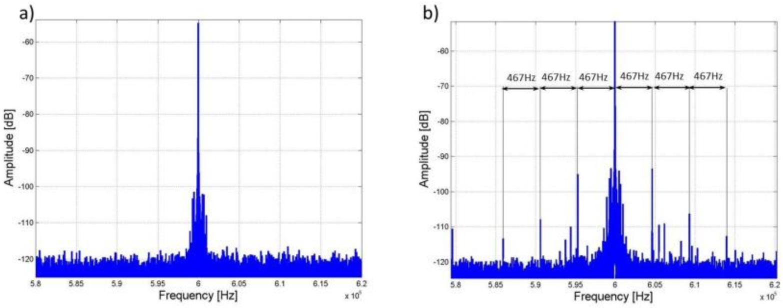

Figure 7. Examples of ultrasonic response power spectra for nonlinear acoustics test: a) undamaged plate, b) damaged plate.

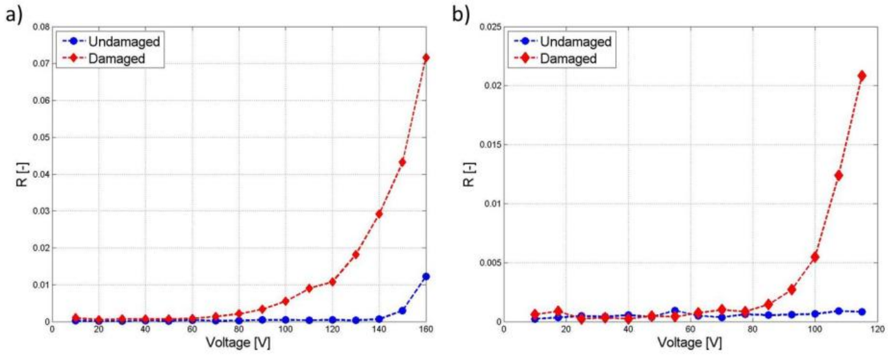

Figure 8. Analysis of modulation intensity – R vs. excitation level for: a) the 2nd vibration mode - 74 Hz, b) the 7th vibration mode - 467 Hz.

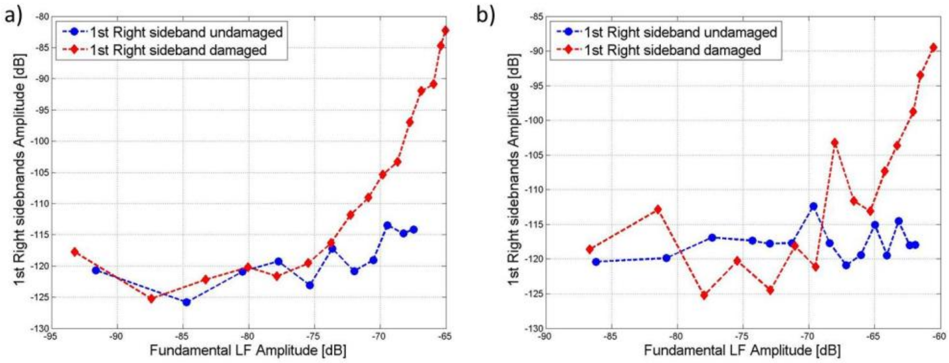

Figure 9. Analysis of the first right sideband amplitude for: (a) the 2nd vibration mode; (b) the 7th vibration mode.

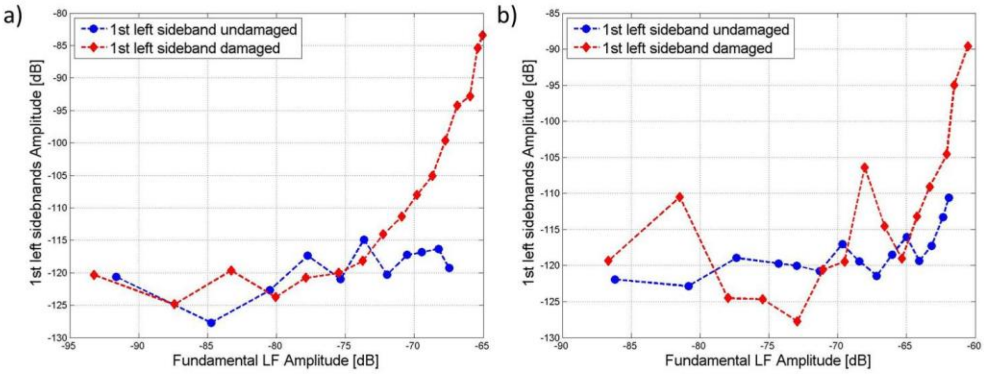

Figure 10. Analysis of the first left sideband amplitude for: (a) the 2nd vibration mode; (b) the 7th vibration mode.

The analysis of the first order sidebands confirms all above results (see Figures 9 and 10). The increase of amplitude level with the growing modal excitation amplitude is significant for both analysed modes. The sideband amplitudes are scattered until some value of low-frequency excitation is reached (-80 dB for the 2nd mode and -65 dB for the 7th mode). For larger values of modal excitation sideband characteristics are less scattered. The same behaviour was previously observed in metallic structures with fatigue cracks [17].

5 Conclusion

The application of nonlinear acoustics for impact damage detection has been demonstrated. The experimental tests were performed for two composite plates. The method used was based on nonlinear vibro-acoustic modulations. Low-profile surface-bonded piezoceramic transducer were used for low-frequency vibration and high frequency ultrasonic excitations. Acoustical responses were acquired using a laser scanning vibrometer measuring out-of-plane vibration. The focus of the work was on modulation intensities due to excitation level. The study demonstrates that the method has a potential for impact damage detection in composites. Modulation sidebands were observed in the power spectrum of acoustic responses when the specimen was damaged. The amplitude of sidebands increased significantly with the low-frequency excitation level for the damaged composite plate.

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References

[1]. Staszewski Wj J., Boller, C. , Tomlinson, G. R, Health Monitoring of Aerospace Structures, Wiley, Chichester, 2004.
[2]. Christian Boller, F. -K. Chang, Y. Fujino, Encyclopedia of Structural Health Monitoring, Wiley, 2009.
[3]. K. Diamanti, J.M. Hodgkinson and C. Soutis, Detection of low-velocity impact damage in composite plates using Lamb waves, Structural Health Monitoring. 3(1) (2004) 33-41.
[4]. D.Alleyne, P.Cowley, “The Interaction of Lamb Waves with Defects”, IEEE Trans. On Ultrasonics, Ferroelectrics, and Frequency Control, vol. 39, N3, May 1992, pp. 381-396.
[5]. M. Meo and M. Zumpano, Nonlinear elastic wave spectroscopy, identification of impact damage on a sandwich plate, Comput. Struct. 71, (2005) 469-474.
[6]. F. Aymerich and W. J. Staszewski, Impact damage detection in composite structures using nonlinear acoustics, Proceedings of the 10th Conference on Deformation and Fracture of Composites (DFC10), Sheffield, UK, 15-17 April 2009.
[7]. K. Van Den Abeele, P.A. Johnson and A.M. Sutin. Nonlinear elastic wave spectroscopy (NEWS) technique to discern material damage. Part I: nonlinear wave modulation spectroscopy. Rev Prog QNDE. 12, 2000, 1, pp. 17–30.
[8]. K. Van Den Abeele, T. Carmeliet, J.A. TenCate and P.A. Johnson. Nonlinear elastic wave spectroscopy (NEWS) technique to discern material damage. Part II: single mode nonlinear acoustic spectroscopy. Rev Prog QNDE. 12, 2000, 1, pp. 31–42.
[9]. P. Duffour, M. Morbidini and P. Cawley. A study of the vibro-acoustic modulation technique for the detection of cracks in metals. J Acoust Soc Am. 119, 2006, 3, strony 1463–1475.
[10]. Z. Parsons and W.J Staszewski. Nonlinear acoustics with low-profile piezoceramic excitation for crack detection in metallic structures. Smart Mater Struc. 2006, 15, pp. 1110–1118.
[11]. Polimeno, U., Meo, M., Almond, D. and Angioni, S., 2010. Detecting low velocity impact damage in composite plate using nonlinear acoustic methods. Applied Composite Materials, 17 (5), pp. 481-488.
[12]. Bentahar M, El Guerjouma R., Monitoring progressive damage in polymer-based composite using nonlinear dynamics and acoustic emission, J Acoust Soc Am. 2009 Jan;125(1):EL39-44.
[13]. F. Aymerich and W. J. Staszewski, Experimental Study of Impact-Damage Detection in Composite Laminates using a Cross-Modulation Vibro-Acoustic Technique, Structural Health Monitoring November 2010 vol. 9 no. 6 pp. 541-553
[14]. D. Donskoy, A. Sutin and A. Ekimov. Nonlinear acoustic interaction on contact interfaces and its use for nondestructive testing. *NDT&E Int.* 2001, Vol. 34, 4, pp. 231–238.

[15]. V.A. Antonets, D.M. Donskoy and A.M. Sutin. Nonlinear-vibro diagnostics of flaw in multilayered structures. *Compos Mater.* 1986, 15, pp. 934–937.
[16]. Sutin, D.M. Donskoy and A.M. Vibro-acoustic modulation nondestructive evaluation technique. *J Intell Mater Syst Struct.* 1998, 9, pp. 765–771.
[17]. A Klepka, W J Staszewski, R B Jenal, M Szwedo, T Uhl, J Iwaniec. Nonlinear acoustics for fatigue crack detection – experimental investigations of vibro-acoustic wave modulations. *Structural Health Monitoring.* 2011, Vol. 25, p. doi: 10.1177/1475921711414236.
[18]. K. Van Den Abeele, P.A. Johnson and A.M. Sutin. Nonlinear elastic wave spectroscopy (NEWS) technique to discern material damage. Part I: nonlinear wave modulation spectroscopy. *Rev Prog QNDE.* 12, 2000, 1, pp. 17–30.
[19]. Johnson P. A., Guyer R. *Nonlinear Mesoscopic Elasticity: The Complex Behaviour of Rocks, Soil, Concrete.* s.l. : Wiley, 2009.
[20]. B.A. Korshak, I.Yu. Solodov, E.M. Ballad. DC effects, sub-harmonics, stochasticity and ‘‘memory’’ for contact acoustic non-linearity. *Ultrasonics.* 2002, Vol. 40, pp. 707-713.
[21]. P.Johnston. The new wave in acoustic testing. *Materials World.* 1999, Vol. 7, 9, pp. 544-46.
[22]. F. Aymerich, W.J. Staszewski. Experimental Study of Impact-Damage Detection in Composite Laminates using a Cross-Modulation Vibro-Acoustic Technique. *Structural Health Monitoring.* 2010, Vol. 9, 6, pp. 541-553.
[23]. E.M Ballada, S.Yu Vezirova, K Pfleidererb, I.Yu Solodovb and G Busse. Nonlinear modulation technique for NDE with air-coupled ultrasound. *Ultrasonics.* 42, 2003, pp. 1031-1036.
[24]. S.N. Jerebtsov Al.A. Kolomenskii and H. A. Schuessler. Characterization of a polycrystalline material with laser-excited nonlinear surface acoustic wave pulses. *Fifteenth Symposium on Thermophysical Properties.* 2003.
[25]. B. J. Ruztamreen, W. J. Staszewski, A. Klepka, T. Uhl. Structural Damage Detection Using Laser Vibrometers. *2nd International Symposium on NDT in Aerospace.* 2010.
[26]. W.J. Staszewski, Z. Parsons. Nonlinear acoustics with low-profile piezoceramic excitation for crack detection in metallic structures. *Smart Mater Struc.* 2006, 15, pp. 1110–1118.
[27]. Klepka A, Jenal R B, Staszewski W J, Uhl T. Fatigue crack detection in metallic structures using nonlinear acoustics – comparative study of piezo-based excitation. *5th ECCOMAS thematic conference on Smart structures and materials SMART'11.* 2011, pp. 444-451.
[28]. H, Weisbecker. Damage detection via 3-D scanning laser vibrometer measurements utilizing the concept of strain compatibility. *MSc thesis, Technical University of Dresden.* 2009.
[29]. Delsanto, P.P. *Universality of nonclassical nonlinearity.* New York : Springer, 2007.
[30]. I.Yu. Solodov, N. Krohn , G. Busse. CAN: an example of nonclassical acoustic nonlinearity in solids. *Ultrasonics.* 2002, Vol. 40, pp. 621–625.
[31]. Donskoy, D., Sutin, A. and Ekimov, A. Nonlinear Acoustic Interaction on Contact Interfaces and its use for Nondestructive Testing. *NDT&E International.* 2001, Vol. 34, 4, pp. 231-238.