Nonlinear Acoustic Imaging of Structural Damages in Laminated Composites

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NONLINEAR ACOUSTIC IMAGING OF STRUCTURAL DAMAGES IN LAMINATED COMPOSITES

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ABSTRACT

The paper describes the application of nonlinear acoustic techniques recently reported in scientific literature for imaging of structural damage in a laminated composite plate. The techniques that have been considered include the local defect resonance technique and the second harmonic imaging technique. The tests are performed on a carbon fiber/epoxy laminated composite plate with barely visible impact damage that was generated in an impact test. The extent of damage is characterized by vibrothermography prior to nonlinear acoustic tests. The paper discusses theoretical background and experimental setup for each measurement technique.

KEYWORDS : *composites, damage detection, vibrothermography, nonlinear acoustics.*

INTRODUCTION

Nondestructive damage detection techniques are constantly evolving to meet the requirements of modern engineering applications. The use of advanced materials and manufacturing processes raises the complexity of inspection and requires an ever increasing accuracy of detection. A good example is the inspection of composite materials which are being adopted for critical structural components at the same time being prone to manufacturing defects and damages during the service period. There is a wide variety of techniques for assessing structural integrity of composites including ultrasound testing, active thermography and radiography, among others [1,2]. Recent years show, however, an increasing interest in novel nonlinear damage detection methods [3-12]. These methods rely on the 'non classical' nonlinear effects that arise due to the presence of damage and are manifested in structural responses. The 'non classical' phenomena include the nonequilibrium dynamics [4], dissipative mechanisms and hysteresis [4], contact acoustic nonlinearity [8], Luxembourg–Gorky effect [9] or memory effect [10]. The effects of these mechanisms in measured structural responses include the presence of higher harmonics whose amplitudes do not decay as fast as in the classical case, generation of subharmonics, hysteresis, instabilities, chaotic dynamics [3,4]. These methods have been applied to a variety of materials including rocks [4], metals [5-10] and composites [11,12] The main advantage of those methods is that they are typically much more sensitive to small damage severities than their linear counterparts, allowing to detect damage on a very early stage of its formation. The main disadvantage is, however, the lack of damage localization capabilities of those techniques. This paper is targeting this issue by investigating the non-classical nonlinear acoustic imaging of structural damage in laminated composites.

A laminated prepreg composite plate with a barely visible impact damage is investigated with use of the nonlinear acoustic imaging techniques recently reported in scientific literature. The methods include the local defect resonance technique (LDR) [13-14] and the second harmonic imaging technique (SEHIT) [15-16]. The non-classical nonlinear effects, including the contact acoustic nonlinearity, are investigated in the frequency domain and spatially mapped on the surface of the plate to localize impact damage.

TEST SAMPLE

The test sample was a laminated composite plate with a barely visible impact damage. The plate was manufactured from carbon/epoxy (Seal HS160/REM) unidirectional prepreg plies. The stacking sequence of the laminate was $[0_3/90_3]_s$. The dimensions of the plates were 150×300×2 mm. The dimensions and details of the plate are shown in Figure 1. The specimens were verified free from manufacturing defects prior to testing. Low velocity impact test was performed on the plate to introduce damage. The plate was simply supported on a rigid post with a rectangular opening in the center and an instrumented drop-weight testing machine was employed to impact the plate in the central location. The plate was impacted with the energy of 3.9 J, which was obtained by selecting the appropriate drop height of the impactor. The absorbed energy was evaluated by measuring the velocities of the impactor immediately before and after the impact.

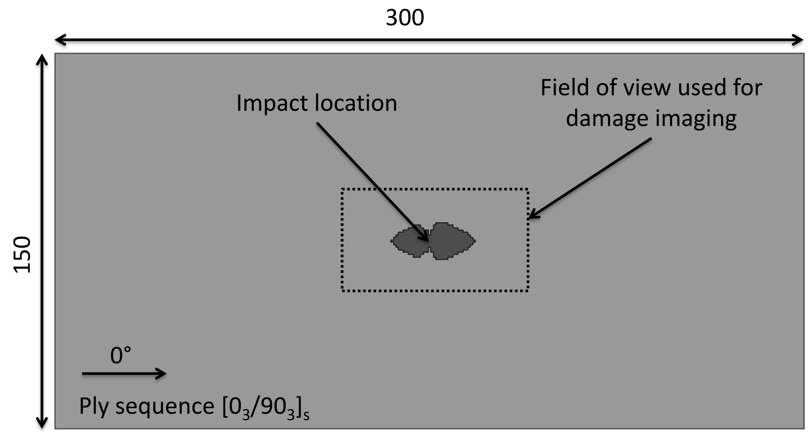

Figure 1. The analyzed composite plate with barely visible impact damage.

VIBROTHERMOGRAPHY

After conducting impact test, the extent of damage in the plate was evaluated using vibrothermography. This method is an active thermographic nondestructive testing (TNDT) method with external excitation [17]. In vibrothermography, the external energy is delivered to the structure by ultrasonic vibrations, as shown in Figure 2. Typically a burst signal with the duration of several milliseconds is used to excite the test sample. High frequency vibrations cause energy dissipation at material discontinuities (i.e. cracks, delaminations) and mechanical energy is converted into heat. Thermographic camera is used to record the surface temperature distribution on the sample. Inference about the existence of damage is performed on the basis of the measured temperature distribution. Vibrothermography is a dark field method where the source of heat is the damage itself, which simplifies the data processing phase to a great extent.

The *Monit SHM* mobile vibrothermographic test system using the 35 kHz ultrasonic excitation column was used to conduct the experiment [18]. The photon detector camera *Cedip Silver 420M* was used to acquire thermal image sequences. The ultrasonic column was exciting the plate for 500 milliseconds and thermographic camera was acquiring the signal at 100 Hz frame rate for 3 seconds.

Results of the vibrothermographic inspection are shown in Figure 3. The figure presents measured temperature on the surface of the plate in the area marked by the dashed line in Figure 1. Background temperature distribution, measured just before the beginning of the test, was subtracted from the results to improve the contrast. There are four different time instances shown in Figure 3. Time t=0 ms corresponds to the start of ultrasonic excitation of the sample. As can be seen the temperature distribution is uniform and only the thermal camera detector noise is present.

At time t=100 ms the vertical surface matrix cracks are becoming visible in the thermal picture. At time t=200 ms a characteristic butterfly like delamination on the 0°/90° interface further from the impact side is revealed. At time t=400 ms the picture starts to become blurred due to the temperature being conducted away from the source, which in case of vibrothermography is the damage itself.

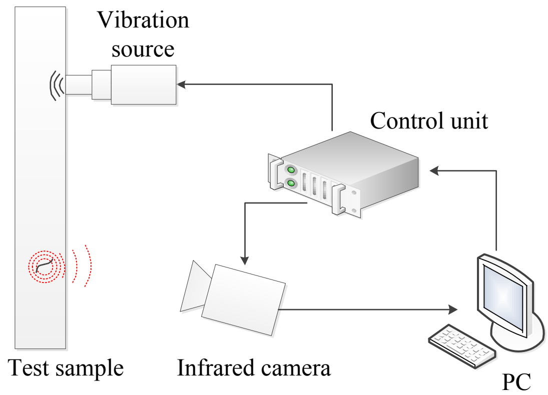

Figure 2. Operation principle of vibrothermography [17].

The area of delamination for the 3.9 J impact identified from the test was approximately 300 mm^2.

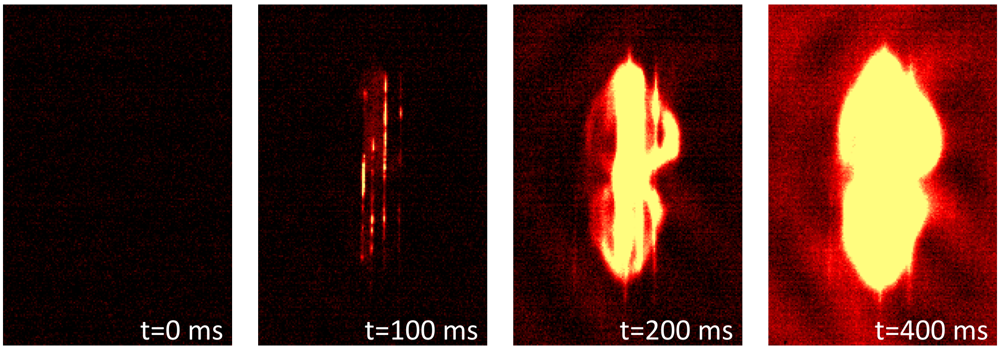

Figure 3. Results of the vibrothermographic measurement on the composite plate – surface temperature distribution at different time instances.

NONLINEAR ACOUSTIC IMAGING

In the next step the damage was investigated with use of two nonlinear testing techniques, namely the local defect resonance technique (LDR) and the second harmonic imaging technique (SEHIT).

Experiments for both methods were performed using the same experimental setup shown in Figure 4. The plate was suspended using elastic cords to simulate free-free boundary conditions. The excitation was applied by a surface-bonded Noliac CMAP4 stack actuator driven by the EC Electronics PAQG signal amplifier. A Polytec PSV-400 scanning laser vibrometer was used for non-contact measurements of vibration responses at 475 points on a 19×25 measurement grid. Excitation frequency for the LDR measurement was identified numerically and experimentally at 30095 Hz [19]. Excitation frequency for the SEHIT measurement was arbitrarily chosen at 13592 Hz which was one of the natural frequencies of the composite plate.

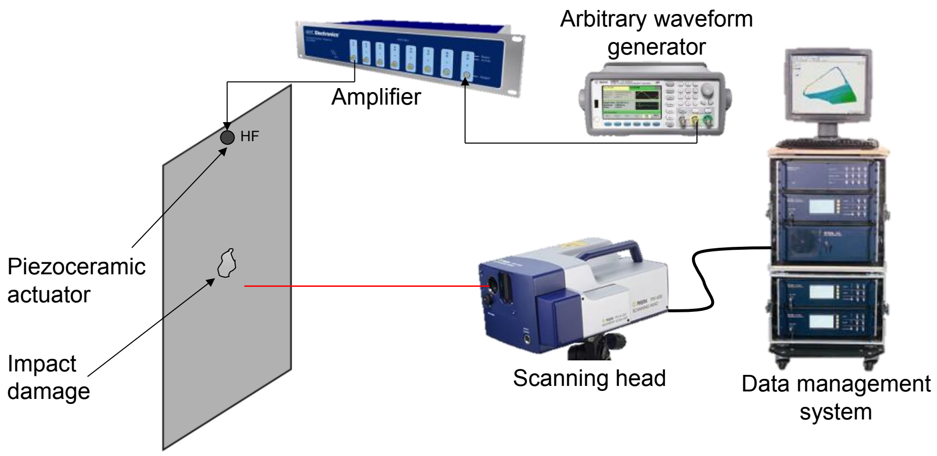

Figure 4. Experimental setup used for the nonlinear acoustic imaging.

The main assumption of the LDR method is that a structural defect has associated resonant frequencies, being a function of damage size and geometry, that can be used to improve the effectivenes of nonlinear wave modulation tests [13,14]. The local resonance of a defect can also be utilised to reveal the location of damage in a nonlinear acoustic test. The assumption is that the amplitude level of higher harmonics in measured response spectra increases dramatically near the location of damage.

To illustrate this the composite plate was excited with a single-harmonic signal at frequency equal to 30095 Hz corresponding to the LDR frequency and the broadband response spectrum was acquired at a number of points. Figure 5 presents the spatial mapping of measured spectral amplitudes, at frequencies equal to the resonant frequency of the defect at 30095 Hz (Figure 5a) and its second harmonic at 60190 Hz (Figure 5b). The amplitudes were mapped at the surface of the plate in the area marked by the dashed line in Figure 1. As can be seen, the location damage can be easily identified in both cases, however, when we consited the higher harmonic response at 60190 Hz the we can see that the contrast is greatly improved.

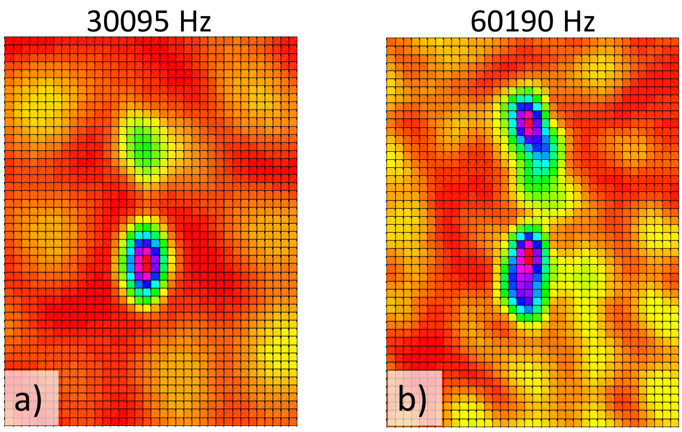

Figure 5. Spatial mapping of measured spectral amplitudes: at frequency equal to the resonant frequency of damage (a) and its second harmonic (b).

The second harmonic imaging technique SEHIT is an alternative approach that can be used for damage imaging [15,16]. The method, similarly to the LDR based imaging, is based on the spatial mapping of higher harmonic amplitudes generated by damage. The generation of higher harmonics can be attributed to a nonlinear relation of strains and stresses in a damaged specimen. The assumption is that the spatial distribution of the ratio between the amplitude of a second harmonic over the amplitude at excitation frequency reveals the location of damage. In contrast to the LDR method, there is however no indication as for the preferred excitation frequency that should be used.

For the SEHIT experiment the modal frequency at 13592 Hz was arbitrarily chosen. The main selection criterion was that this frequency had a clear peak in the frequency spectrum. Figure 6 presents the result of the SEHIT experiment. Similarly to the LDR results in Figure 5, the picture presents the spatial mapping of measured spectral amplitudes, at frequencies equal to the excitation frequency at 13592 Hz (Figure 6a) and the ratio of its second harmonic at 27184 Hz and the excitation frequency (Figure 6b). Again, the amplitudes were mapped at the surface of the plate in the area marked by the dashed line in Figure 1. The picture in Figure 6a presents the mode shape corresponding to the natural frequency used for excitation with no indication about the presence or location of damage. The picture in Figure 6b, however, shows an increased response level at the central location of the plate corresponding to the location of damage. The shape of damage cannot be however easily identified. Moreover, as reported in [19], a different choice of the excitation frequency for SEHIT may result in an even less clear picture of damage.

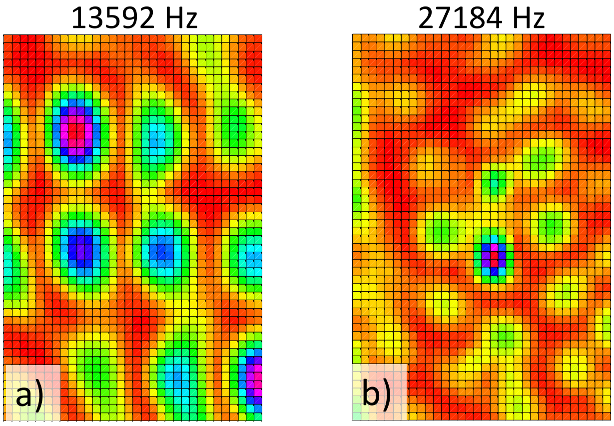

Figure 6. Spatial mapping of measured spectral amplitudes: at natural frequency at 13592 Hz (a) and the ratio of the amplitude of a second harmonic over the amplitude at excitation frequency (b).

CONCLUSIONS

The paper demonstrated the application of two nonlinear acoustic techniques to identify the presence and location of structural damage in a laminated composite plate. The results were compared with vibrothermographic inspection of the test specimen. The results show that the local defect resonance (LDR) based imaging clearly indicated the existence and the location of a barely visible impact damage in the analyzed composite plate. The results of second harmonic imaging technique (SEHIT) imaging were less clear, but the presence of damage could still be identified. Despite its higher effectiveness, the LDR based imaging technique is more difficult to apply than the SEHIT as it requires the knowledge of the resonant frequency of damage. Further work is planned in this area to improve the effectiveness of the nonlinear acoustic damage imaging techniques.

ACKNOWLEDGMENTS

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REFERENCES

[1] Stepinski T., Uhl T. and Staszewski W.J., (Eds.), Advanced Structural Damage Detection: From Theory to Engineering Applications, Wiley, 2013.
[2] Staszewski W.J., Boller C., Tomlinson G. R., (Eds.), Health Monitoring of Aerospace Structures, Wiley, 2004.
[3] Delsanto P.P. (Ed.), Universality of nonclassical nonlinearity: applications to non-destructive evaluations and ultrasonics, Springer, 2006.
[4] Guyer R.A., Johnson P.A., Nonlinear Mesoscopic Elasticity: The Complex Behaviour of Rocks, Soil, Concrete. Wiley-VCH; 2009.
[5] Van Den Abeele K., Johnson P.A., Sutin A., Nonlinear Elastic Wave Spectroscopy (NEWS) Techniques to Discern Material Damage, Part I : Nonlinear Wave Modula tion Spectroscopy (NWMS)," Res Nondestr Eval, vol. 12, pp. 17–30, 2000.
[6] Donsky D., Sutin, A., Ekimov, A., Nonlinear acoustic interaction on contact interfaces and its use for nondestructive testing, NDT&E Int., 34(4):231–238, 2001.
[7] Jhang K., Nonlinear Ultrasonic Techniques for Non- destructive Assessment of Micro Damage in Material : A Review, Precis. Eng., 10(1):123–135, 2009.
[8] Solodov I.Y., Resonant Acoustic Nonlinearity of Defects for Highly-Efficient Nonlinear NDE," J. Nondestruct. Eval., 2014.
[9] Zaitsev V., Gusev V., Castagnede B., Observation of the Luxemburg–Gorki effect for elastic waves, Ultrasonics, 40(1) :627–631, 2002.
[10] Zaitsev V., Gusev V., Castagnede B., Thermoelastic mechanism for logarithmic slow dynamics and memory in elastic wave interaction with individual cracks, Phys Rev Lett, 90, 2003.
[11] Klepka A., Pieczonka L., Staszewski W.J., Aymerich F., Impact damage detection in laminated composites by non-linear vibro-acoustic wave modulations, Compos. Part B Eng., 2013.
[12] Pieczonka L, Staszewski W.J., Uhl T., Investigation of Nonlinear Vibro-Acoustic Wave Modulation Mechanisms in Composite Laminates, Key Eng. Mater., vol. 569–570, pp. 96–102, 2013.
[13] Solodov I.Y. et al., 2011. A local defect resonance to enhance acoustic wave-defect interaction in ultrasonic nondestructive evaluation. Applied Physics Letters, 99(21):211911.
[14] Solodov I.Y. et al., 2012, A Local Defect Resonance to Enhance Wave-Defect Interaction in Nonlinear Spectroscopy and Ultrasonic Thermography. 18th World Conference on Nondestructive Testing, 16-20 April 2012, Durban, South Africa.
[15] Polimeno U., Meo M., Almond D.P., Smart Nonlinear Acoustic Based Structural Health Monitoring System. Advances in Science and Technology, 56:426–434, 2008
[16] Polimeno U. et al., Detecting Low Velocity Impact Damage in Composite Plate Using Nonlinear Acoustic/Ultrasound Methods. Applied Composite Materials, 17(5):481–488, 2010.
[17] Pieczonka, L. and Szwedo, M., 2013. Vibrothermography. In T. Stepinski, T. Uhl, W. J. Staszewski, (Eds.), Advanced Structural Damage Detection: From Theory to Engineering Applications. Wiley, pp. 233–261.
[18] Monit SHM LLC. 2014, http://www.monitshm.pl/en/index.php?loc=vibrothermography.
[19] Klepka A., Pieczonka L., Staszewski W.J., Aymerich F., Application of Local Defect Resonance Method to structural damage detection, in the proceedings of the International Workshop on Structural Health Monitoring, Stanford, 2013.