Non-linear acoustics techniques for NDT

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Abstract

Non-linear acoustics is an emerging field of non-destructive testing, offering a variety of methods with the particular attraction of early stage detection of flaws and damage in structures.

This paper reviews the field of non-linear acoustic NDT and discusses the potential advantages and limitations of each technique in the context of conventional NDT methods.

1. Introduction

The recent emergence from the academic realm of non-linear acoustic (NLA) techniques offers interesting new possibilities for non-destructive testing (NDT), in particular the clear ability of NLA methods to detect damage at a much earlier stage in its development than most conventional NDT methods. With the increasing commercial adoption of new structures and materials, NDT capabilities are being re-evaluated. Even within the field of NLA there are several different NDT offerings and we seek here to summarise methods and their capabilities. Johnson [1] has termed the NLA technique *Nonlinear Elastic Wave Spectroscopy*, or NEWS. In general, the approaches subdivide into one of two categories: excitation of resonances in defects caused by harmonics or subharmonics of that resonance, or generation of non-linear behaviour caused by 'clapping' or stick-slip friction behaviour in and around a defect. The latter generally relates to a high-aspect-ratio defect, such as a delamination or crack, whereas the former might also apply to more spheroidal phenomena such as voids. In addition there is a third significant non-linear phenomenon, which we describe in Section 3.4 (Resonance Shift and Resonance Drift).

2. Principles of non-linear acoustic NDT

Conventional linear materials conform to Hooke's Law, exhibiting a linear relationship between stress and strain. It has been shown in the literature [2,3] that structures containing certain kinds of flaw or defect exhibit non-linear stress-strain behaviour, Figure 1. Solodov describes this as a "mechanical diode" [3].

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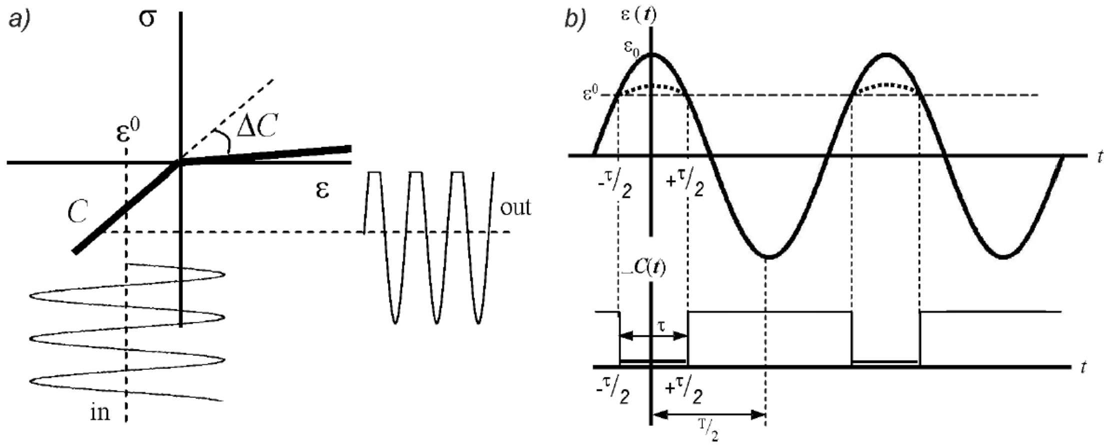

Figure 1. a) Non-linear stress-strain curve and (b) waveform distortion (upper) and stiffness modulation (lower) for clapping non-linearity (after Solodov [3]).

A typical non-linear defect morphology would be that of a crack or a delamination, where a ‘clapping’ mechanism of alternate opening and closing is set up under cyclic compression and tension caused by, for example, a continuous sine wave. Here the defect stiffness under compression is much higher than that under tension. Given the likelihood that such a defect will have an elliptical profile in the open position, there is the additional complexity that it might be excited by more than one frequency (or a range of frequencies) due to variable stiffness across the defect profile (Figure 2). For simplified modelling purposes these high-aspect-ratio defects are usually represented by one spring and one damper (Figure 3).

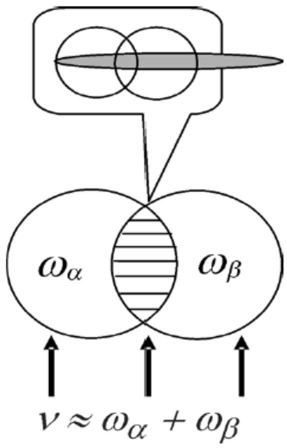

Figure 2. Representation of a crack as a pair of coupled oscillators. If the frequency of the excitation is $\nu \approx \omega\alpha + \omega\beta$, the difference frequency components $\nu - \omega\alpha \approx \omega\beta$ and $\nu - \omega\beta \approx \omega\alpha$ provide cross excitation of the coupled oscillators. (after Solodov [3]).

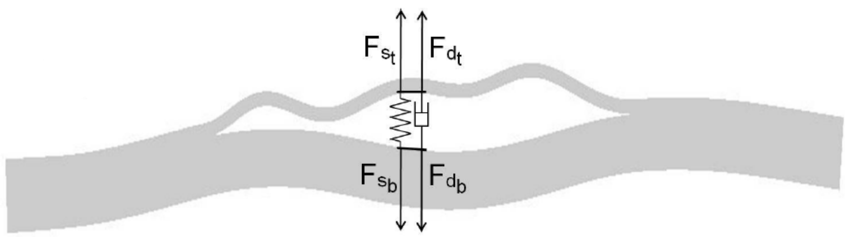

Figure 3. Spring and damper elements implementing a simple model of a delamination (after Delrue [4]).

Solodov has argued that a friction mechanism will give rise to a different non-linear stress-strain behaviour. Consider a shear wave propagating past a defect. Low amplitude vibration will not overcome the static friction force. At a particular amplitude the interface will slip and stiffness will reduce, probably dramatically. This phenomenon is independent of direction of shear motion and thus gives rise to the stress-strain relationship of Figure 4 and consequently only odd harmonics are generated.

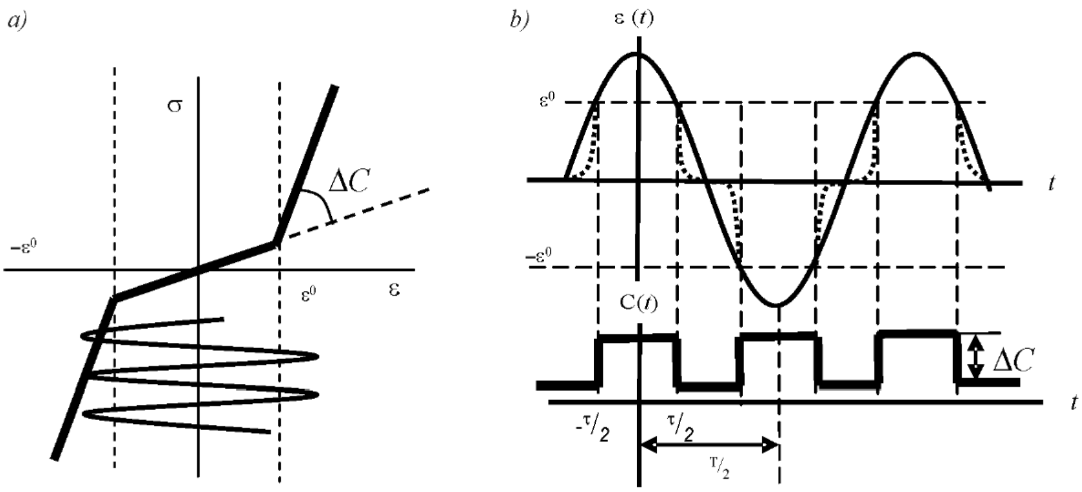

Figure 4. a) Non-linear stress-strain curve and (b) waveform distortion (upper) and stiffness modulation (lower) for stick-slip friction-based non-linearity (after Solodov [3]).

Van den Abeele et al. [2] have concisely summarised the various non-linear permutations (Figure 5).

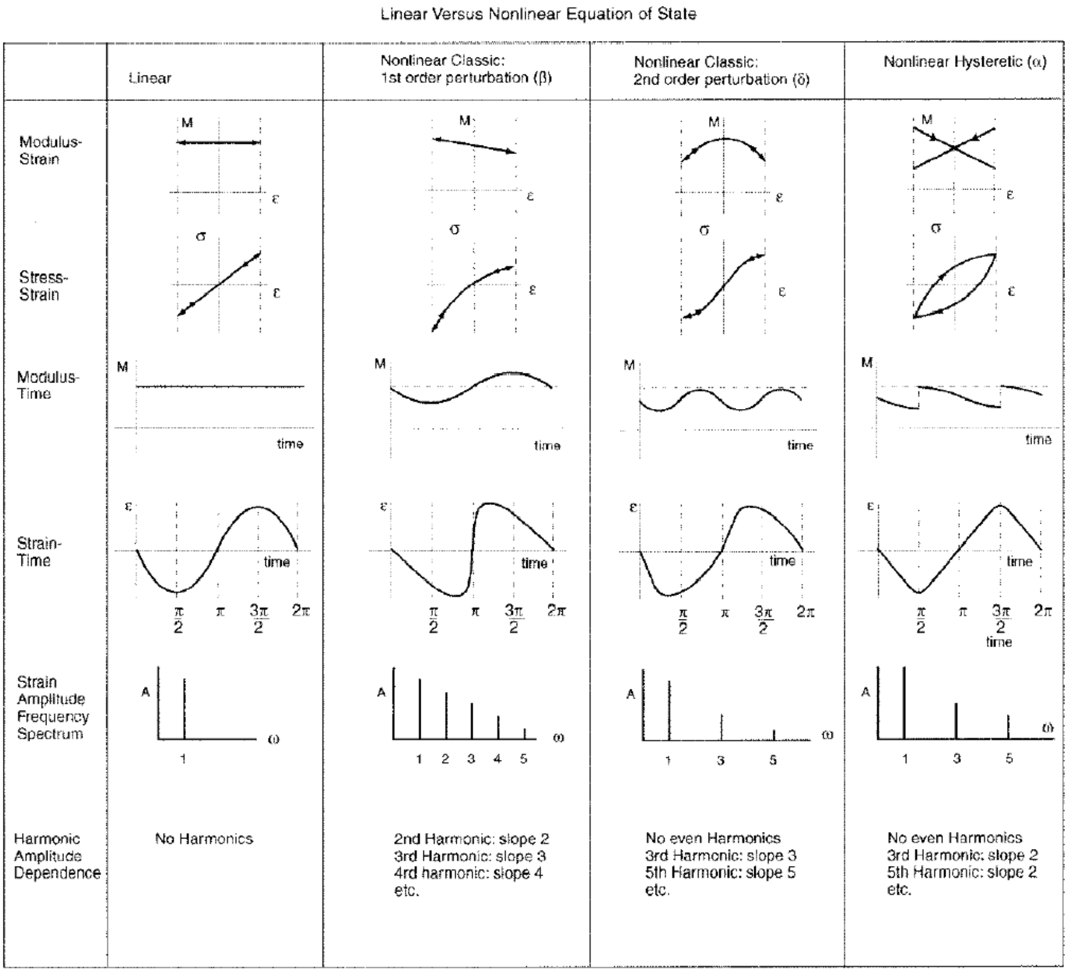

Figure 5. The various non-linear manifestations of structural defects (after Van den Abeele [2]).

Local Defect Resonance

Solodov discusses the phenomenon he terms *local defect resonance* [3], whereby a defect is induced into resonance by exciting the parent structure at a frequency which might be significantly lower than the resonance frequency of the defect (and not necessarily a modal frequency of the parent structure). In the example of Figure **6** the 10th harmonic is clearly shown to provide the best definition of the defect.

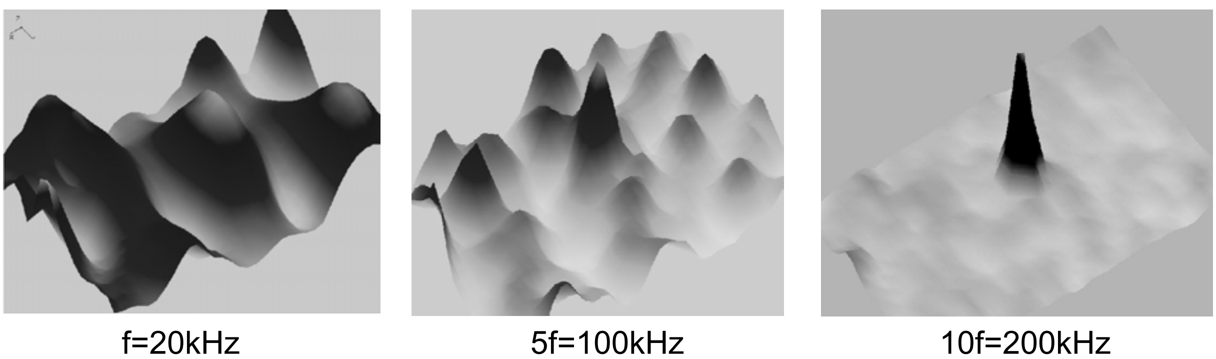

Figure 6. Resolution of defects using high-order harmonics (after Solodov [3]).

Solodov has further demonstrated that vibration even from sub-surface defects will cause displacement at the surface of the structure and thereby radiate efficiently into surrounding air, allowing scope for optical, thermal or non-contact acoustic receivers [3]. Optical (such laser vibrometers or speckle-pattern interferometers and thermal (such as infrared cameras) receivers offer the capacity for high-speed data acquisition over large surfaces, albeit at a relatively high cost and with some vulnerability in harsh environments and susceptibility to reflective properties of the surface. Acoustic receivers will generally require longer data capture times but are likely to be much cheaper and more robust.

3. NLA methods

3.1. Single-frequency harmonic

This method consists of a single-frequency excitation and detection of multiple harmonics due to a defect. Armitage [5] has illustrated the capacity to detect compressive damage in concrete cylinders (Figure 7) and impact damage in carbon fibre panels (Figure 8). In the former case, damage was detected at 20% of Ultimate Compressive Strength (UCS), whereas conventional linear NDT techniques do not detect onset of failure until around 80% UCS.

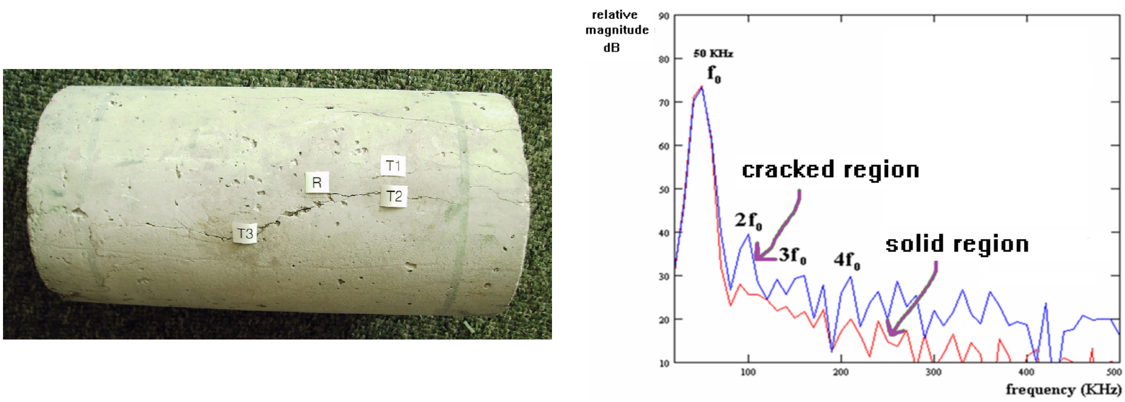

Figure 7. Detection of compressive damage in concrete by the single-frequency harmonic method (after Armitage [5]).

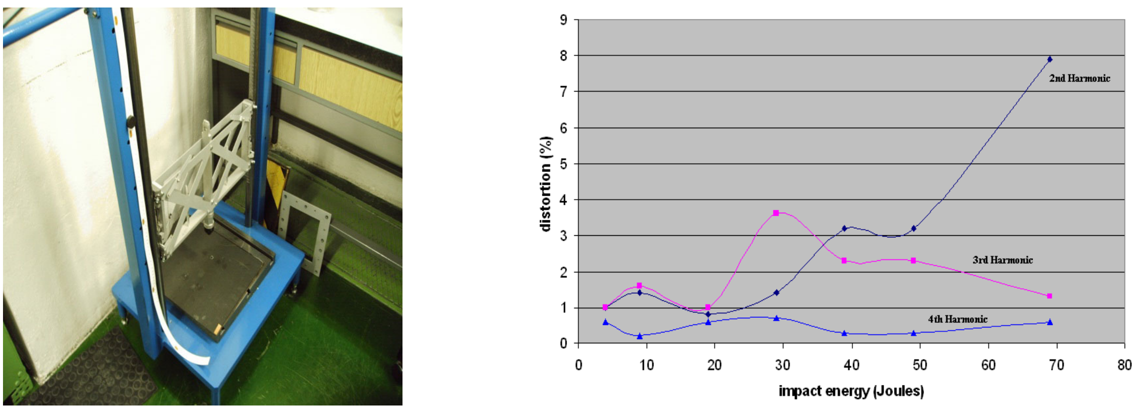

Figure 8. Detection of impact damage in CFRP plate by the single-frequency harmonic method (after Armitage [5]).

3.2. Dual-frequency

Two distinct variants exist: the first we term *dual-frequency intermodulation*, and the second we term *dual-frequency amplitude modulation*.

3.2.1. Dual-frequency intermodulation

Two discrete frequencies f_1 and f_2 are injected into the structure and intermodulation products (e.g. f_2-f_1, f_2+f_1, $2f_2$+f_1, etc.) are produced at the receiver (output) if non-linear sources are present in the structure (Figure 9).

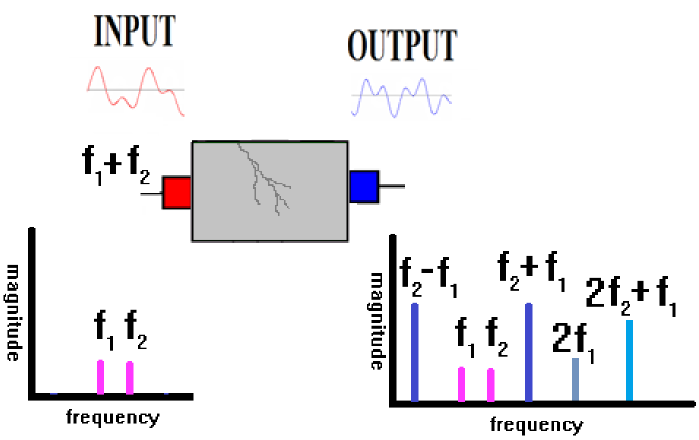

Figure 9. Dual-frequency intermodulation (after Armitage [5]).

The method can be implemented with dissimilar frequencies (LF/HF mode) such as that shown by Van Den Abeele et al. to detect cracks in Plexiglas [2] (Figure 10), or with two similar frequencies (HF/HF mode) such as that employed by Armitage [5] to detect early-stage failure in a safety-critical aircraft component (Figure 11). The former offers the ability to inject higher strain energy at the lower frequency (with potential benefits in signal-to-noise ratio), whereas the latter provides the capability to locate the defect more precisely by exploiting the overlap between the two excitations (Figure 12).

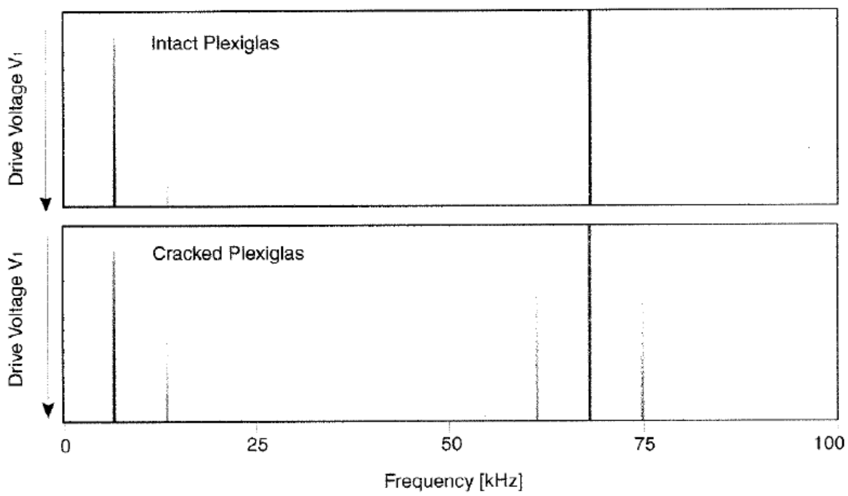

Figure 10. Dual-frequency (7kHz and 70kHz) intermodulation detection of damage in Plexiglas (after Van Den Abeele[2]).

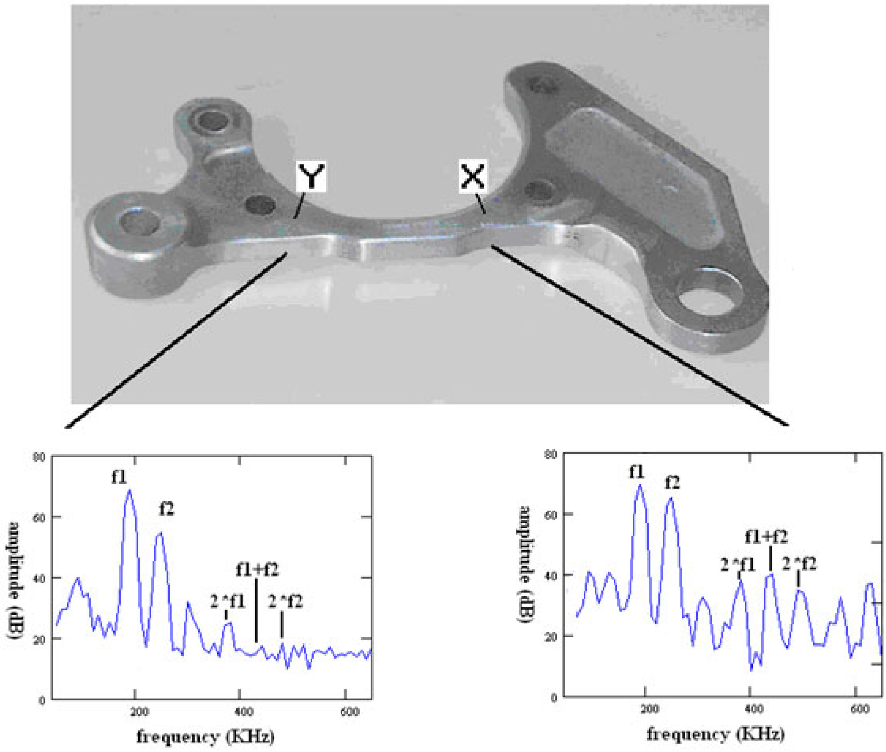

Figure 11. Dual-frequency (184kHz and 240kHz) intermodulation detection of early-stage failure in a safety-critical aircraft component (after Armitage [5]). After 20,000 stress cycles, a defect is indicated at point X. The component failed at this point after 120,000 cycles.

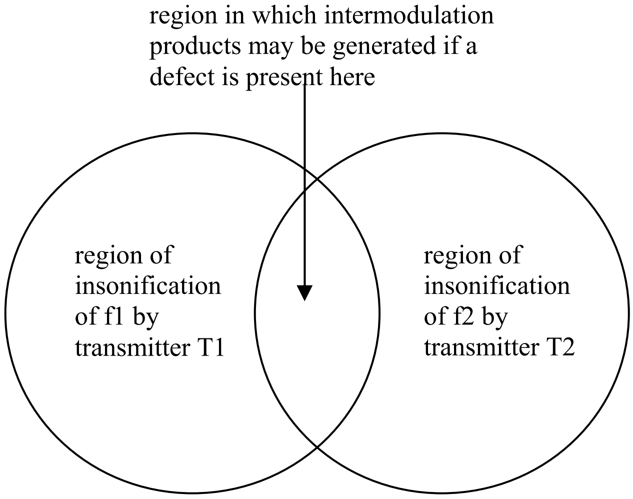

Figure 12. The ability of dual-frequency intermodulation to locate defects through overlapping regions of insonification.

3.2.2. Dual-frequency amplitude modulation

A continuous low-frequency 'pump' wave is used to cause cracks to open and close, and a high-frequency tone burst 'probe' is injected into the structure. Kazakov et al. describe the use of this method with a moving-window synchronous detector to extract reflected HF energy from the crack [6]. This energy varies according to the relative phase of the LF pump and hence provides information regarding the location of the crack (and size, if the HF transmitter is moved along one or more sides of the structure).

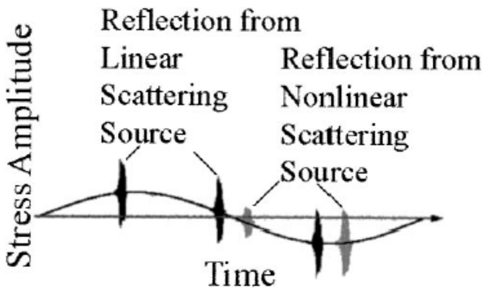

Figure 13. Amplitude modulation of HF 'probe' pulse by LF 'pump' wave (after Kazakov et al. [6]).

3.3. Pulse inversion

This technique is particularly suited to thin, layered, low-loss structures and involves energising the testpiece with a broadband pulse and then, after allowing the structure to return to equilibrium, exciting the structure again with a phase-inverted (180° phase-shifted) version of the same pulse. By adding together the two received signals, any difference in response is exposed. If the structure is linear, there will be no difference signal. If the structure is non-linear (i.e. defective), the difference signal will contain energy. Mattei illustrates the technique in Figure 14 and has demonstrated it in an immersion scanner [7]. Armitage has successfully implemented the method directly upon a carbon fibre laminate (Figure 15) [5].

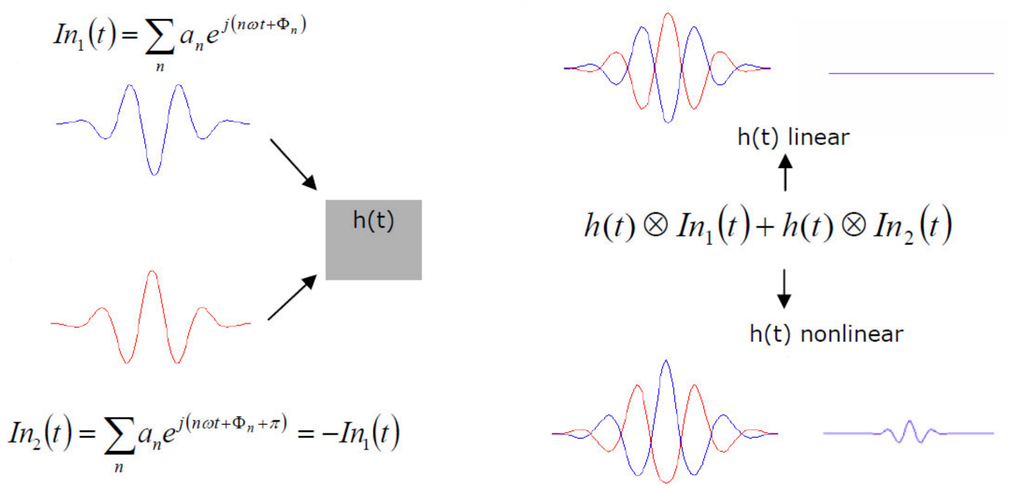

Figure 14. The principle of the pulse inversion method (after Mattei [7]).

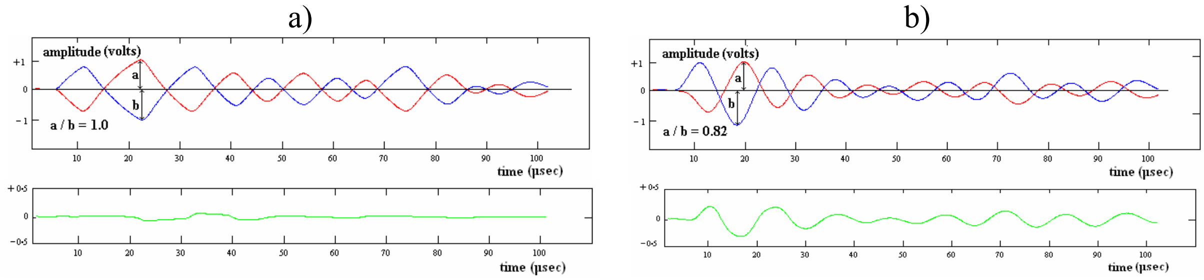

Figure 15. Response of carbon fibre laminate to positive pulse (blue) and negative pulse (red) and the summation of these responses (green): a) intact panel; (b) damaged panel (after Armitage [5]).

3.4. Resonance Shift and Resonance Drift

Van Den Abeele et al. discuss the phenomenon of resonance shift in defective structures [8]. In an intact resonant system, the resonance frequency reduces very slightly with increase in excitation amplitude. If the system contains compliant defects (such as a crack), the resonance frequency reduces much more markedly with increasing strain (Figure 16).

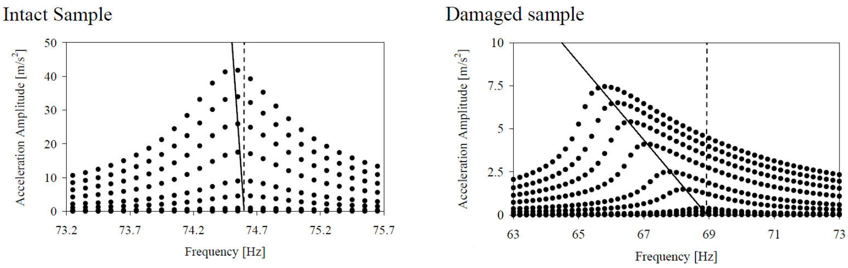

Figure 16. Measured resonance curves at varying input (strain) levels (after Van Den Abeele [8]).

By comparing the relative shifts in resonance, the integrity of a testpiece may be assessed. The above method involved a series of stepwise measurements of resonance frequency at given loads and is relatively slow. Armitage [5] has produced a system which uses a phase-locked loop to track the subtle increase in resonance after a defective structure has been excited and the excitation is then suddenly removed (Figure 17). We call this latter, real-time, method the *resonance drift* technique.

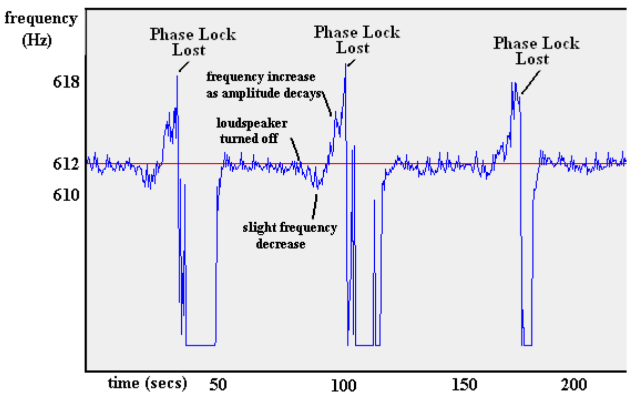

Figure 17. Real-time measurement of resonance frequency drift in a flawed structure using a phase-locked loop (after Armitage [5]).

3.5. Time-Reversal Non-linear Elastic Wave Scattering (TR-NEWS)

This method exploits the principle of reciprocity, using non-linear energy radiated by a defect to locate it within a structure by time-reversing the signal arriving at the receiver transducer(s), and returning this as a stimulus from the receivers (now used as transmitters) [9]. The non-linear component of energy will automatically return to the defect. Armitage [5] illustrates the principle, as shown in Figure 18.

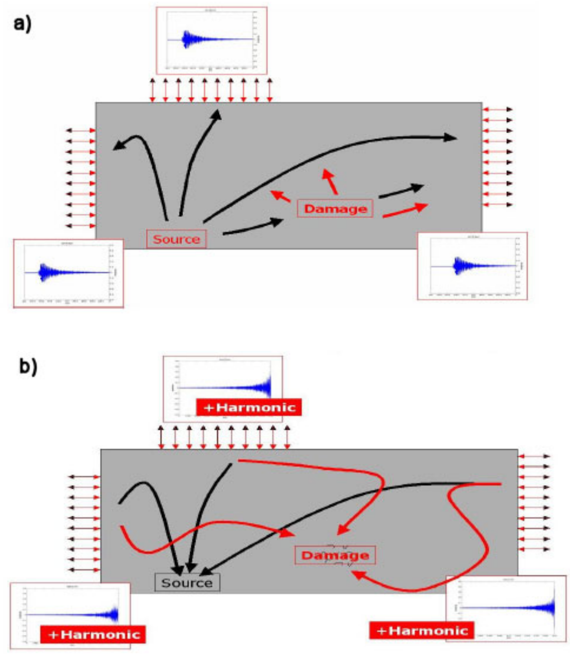

Figure 18. a) In a structure containing a non-linear defect, harmonics will be generated at the damage site. b) Transmitting back the time-reversed signals will result in two concentrations of energy – one at the original source site and the other (harmonics) at the defect (after Armitage [5]).

Van den Abeele et al. [10] have demonstrated a further improvement to the technique by filtering the original stimulus from the time-reversed signal, resulting in improved signal-to-noise in the detection of the defect.

3.6. Conclusion

This paper has discussed a range of non-linear techniques available for non-destructive testing and their attendant attractions for the early detection of defects or imminent failures in structures. Many of these methods are now maturing and offer particular advantages in safety-critical applications and other fields where flaws must be detected at the earliest possible opportunity.

3.7. References

[1] P.Johnson, *The new wave in acoustic testing*, J. Inst. Mater. 7, pp.544-546, 1999.
[2] K.E.-A.Van Den Abeele, P. A. Johnson, A. Sutin, *Nonlinear ElasticWave Spectroscopy (NEWS) Techniques to Discern Material Damage, Part I: Nonlinear Wave Modulation*, Res. Nondestr. Eval. 12, pp.17–30, 2000.
[3] I.Solodov, D.Döring, G.Busse, *New Opportunities for NDT Using Non-Linear Interaction of Elastic Waves with Defects*, J. Mech. Eng. 57 (3), pp.169-182, 2011.
[4] S.Delrue, K.E-A.Van Den Abeele, *Three-dimensional finite element simulation of closed delaminations in composite materials*, Ultrasonics 52, pp.315–324, 2012.
[5] P.R.Armitage, *New ultrasonic methods for detecting damage in metals and composite materials*, Ph.D. thesis, University of Exeter, 2009.
[6] V.V.Kazakov, A.Sutin, P.A.Johnson, *Sensitive imaging of an elastic nonlinear wave scattering source in a solid*, Appl. Phys. Lett. 81, pp.646–648, 2002.
[7] C.Mattei, in *Health monitoring of aircraft by nonlinear elastic wave spectroscopy*, AERONEWS deliverable D3, EC sixth framework AT3-CT-2003-502927, 2008.
[8] K.E-A.Van Den Abeele, A.Sutin, J.Carmeliet, P.A.Johnson, *Micro-damage diagnostics using nonlinear elastic wave spectroscopy (NEWS)*, NDT&E Int. 34, pp.239-248, 2001.
[9] M.Fink, *Time-reversed acoustics*, Sci. Am., pp.91-91, 1999.
[10] K.E-A.Van Den Abeele, P.Y.Le Bas, in *Health monitoring of aircraft by nonlinear elastic wave spectroscopy*, AERONEWS deliverable D3, EC sixth framework AT3-CT-2003-502927, 2008.