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Design, development and testing of multi-functional non-linear ultrasonic instrumentation for the detection of defects and damage in CFRP materials and structures

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Abstract

A multi-functional non-linear ultrasonic testing approach is presented for in-situ and ex-situ detection of a variety of defects (e.g. micro-cracking, delamination and disbonding) induced by various damage mechanisms (stress, impact, heat) in CFRP materials and structures. Such multi-functionality is provided via programmable and re-configurable instrumentation that incorporates a wide range of non-linear ultrasonic testing regimes, including harmonic and overtone generation, inter-modulation product generation, resonant frequency shift and pulse-inversion techniques. The capabilities of this multi-functional approach to defect detection are demonstrated by examining CFRP samples subjected to various forms of damage, specifically stress, impact and heat induced damage. We show that the multi-functional non-linear approach is well-suited to the detection of such forms of damage and that the pulse-inversion technique, largely 'ignored' in the CFRP literature, potentially provides a powerful, but as yet un-tapped, simple and effective route to the defect and damage detection.

Keywords: CFRP; B:Defects; B:Non-linear behaviour; D:Ultrasonics; D:Non-destructive testing

1. Introduction

Carbon fibre composites are of increasing importance, particularly in the aerospace industry, due to their lightweight and high strength. Indeed, up to 50% of the primary structure (fuselage and wings) of Boeing's new 787 'Dreamliner' is made from composite materials. As with all materials, the strength of carbon fibre composites can be compromised by defects caused by various forms of damage and fatigue during service, and/or by faulty manufacturing. The commonest types of induced defects, at least in CFRP materials (the focus of this paper) are micro-cracking, delamination and disbonding. Unfortunately such defects might not be identifiable by visual inspection; it is nevertheless important that they be located and monitored to prevent failure of the affected part or component. Various non-destructive testing (NDT) methods, such as electrical, X-ray imaging and tomography, thermography, acoustic emission and ultrasonic inspection, have therefore been developed for the detection of defects in CFRP materials, components and structures [1-10]. Of these, ultrasonic NDT is probably the most widespread, with linear ultrasonic C-scan imaging and Lamb-wave measurement techniques being the most well-known [8, 11-14]. These well-established linear acoustic methods rely on the measurement of the reverberation, reflection, scattering, transmission or absorption of acoustic energy. The presence of a defect changes the phase or amplitude of the 'interrogating' signal, while its frequency content remains unchanged. However, some types of defects, such as 'closed' defects or defects at the interface between materials with very dissimilar acoustic impedance (which might therefore mask any impedance mis-match arising from cracks or voids), may not be easily discerned by such linear techniques [15,16]. Various *non-linear* ultrasonic NDT approaches have therefore been developed to probe for the defects and damage in CFRP materials and other composites. Non-linear techniques correlate the presence and characteristics of a defect with acoustic signals that have changed in frequency or frequency content. This change is due to the non-linear transform of the acoustic energy by a defect; material regions containing cracks, fractures, delaminations and disbonds have a relatively large non-linear response to acoustic signals. For example, when a sinusoidal acoustic wave is incident upon a crack the wave can change the contact area, increasing it in compression and decreasing it in tension; the crack closes under compression and opens out under tension. This in turn leads to a non-linear stress-strain relationship in the region of the crack, and a non-linear response to the 'interrogating' acoustic wave.

Various non-linear methods have been developed in recent years for defect detection in CFRP materials. The most common include harmonic and overtone generation [15, 16], inter-modulation product generation [17] and resonant frequency shift [18,19]. Of these approaches, that of harmonic generation is the longest established, having started in the 1970's and initially concentrating on second harmonic generation only [20]. The second harmonic generation technique has recently been combined with conventional C-scan imaging to provide a form of non-linear C-scan acoustic microscope for the imaging of fibre/matrix disbond and matrix cracking in CFRP plates [15]. Other researchers have used much higher order harmonics for the visualisation of defects in an attempt to improve the sensitivity of detection; for example Krohn et al. used the 5th harmonic to visualise impact damage in CFRP samples, but also used the 2nd harmonic for the visualisation of heat induced damage [16]. Inter-modulation product generation is an alternative and potentially more sensitive non-linear method for defect detection in composites, and is based on the monitoring of non-linear wave mixing in the material. In the most common inter-modulation approach, the excitation signal consists of two sinusoidal signals of different frequencies (f_1 , f_2) added together, while the detector 'looks' for non-linear signals at the sum ($f_1 + f_2$) and difference ($f_1 - f_2$) frequencies and at twice the individual excitation frequencies ($2f_1$, $2f_2$). While the use of the inter-modulation product generation approach has been reported in various materials (e.g. plexglass, metals, ceramics) [17, 21], its use for the investigation of defects in CFRP does not seem to have been widely reported. Of the other non-linear methods, those based on non-linear resonance techniques, that investigate the resonance behaviour of objects under amplitude-dependent response, have probably received the most attention when it comes to CFRP defect detection [18, 22].

Although, as pointed out above, a number of non-linear methods for have been investigated for the detection of faults and fatigue in carbon-fibre composites, there does not seem to be a universally agreed rationale for which technique is best suited to the detection of which type of defect. Furthermore, even if such a rationale were to exist, real-world samples will potentially contain a variety of defects (e.g. impact damage, micro-cracking, heat damage, delamination and disbonding) such that no single non-linear testing technique will be the optimum inspection choice in all circumstances. Clearly what is needed for the reliable and comprehensive assessment of damage and fatigue in CFRP materials is a multi-functional non-linear ultrasonic testing approach. Such multi-functionality is entirely feasible using a modern approach to the design of programmable and re-configurable instrumentation. In this paper therefore we describe the design of novel multi-functional instrumentation that incorporates all the main non-linear ultrasonic testing regimes, together with the application of the developed instrument to the detection of various forms of damage (specifically stress induced damage, impact damage, heat-induced damage) in CFRP materials and structures.

2. Instrument design

The basic configuration of the non-linear ultrasonic test instrumentation is shown in Fig. 1. The transmitter and receiver modules (which are attached to specially designed piezoelectric transducers that are described in more detail later), are connected to a smart control unit that, together with special-purpose (Windows-based) software loaded on the PC, allows the user to select suitable non-linear testing modes for the specific sample/defect to be investigated. The non-linear modes available to the user include (i) harmonic and overtone generation, (ii) pulse-inversion response, (iii) inter-modulation product generation and (iv) frequency sweep response. In this paper we in particular describe the operation of the system using modes (i) and (ii) for the detection of damage to aeronautical CFRP materials and structures caused by impact, thermal or tensile loading. Such modes are suited to the detection of a wide-range of surface, near-surface and embedded defects, including voids, cracks, delaminations and disbonding. The operating frequency, transmitter power, sampling rate, recording duration and transducer locations for any particular mode are determined by the required spatial and spectral resolution, which in turn is related to the size and type of object or structure that is to be investigated: for example, small objects will require the use of higher frequencies and sampling rates while larger objects will require the use of lower frequencies where the acoustic energy, being less attenuated, will propagate further into the material under test. For the specific samples investigated in this work, i.e. small-scale CFRP laminate plates and a large-scale CFRP-Nomex® honeycomb structure that formed part of a helicopter rotor blade, interrogating signals of 130 kHz and 50 kHz respectively were used. More generally the diverse needs of different sample and testing conditions are accommodated in our instrument by a the provision of a high power (up to 20 W) wideband transmit transducer (see §2.1), a wideband, high-gain (up to 48dB with automatic gain control) receiving transducer system, a high signal sampling rate with high-precision analogue to digital conversion (to 50 M samples/second with 12-bit converter) and purpose-built hardware and software signal processing functions.

2.1 Transducer design

For non-linear acoustic testing the performance requirements of transducers are in general more onerous than for conventional linear ultrasonic approaches. In particular, for non-linear testing the transducers themselves must not introduce any significant distortion in the acoustic wave, since such distortions would potentially mask the detection of distortions generated by defects and damaged regions (the basis of non-linear methods). The receiving transducer must also function over a wide range of frequencies and have a flat frequency response, so enabling proper detection of the amplitude of harmonics, over-tones, inter-modulation frequencies etc. Ideally the transducers should also be able to be used on a wide variety of materials and should be robust, reliable and cost-effective.

To meet the above requirements we have designed and fabricated our own wideband transducers, shown in Fig. 2, based on piezoelectric active elements. To optimise the performance of these transducers consideration must be given to the mechanical properties of the front face and backing materials. Of particular importance is acoustic impedance matching; for efficient transfer of acoustic energy, the characteristic acoustic impedance of the transducer should be close (ideally identical) to that of the material under test (the acoustic load). Here we chose a backing material made from an epoxy-tungsten composite. By varying the amount of tungsten powder it is possible to vary the acoustic impedance of the backing plate. In this prototype transducer the backing plate was designed to have an acoustic impedance of 12 MRayls, a good match for many CFRP and related materials [23]. The transducer front face was made from the glass ceramic material Macor, also with an acoustic impedance of 12 MRayls [24], matching that of the backing plate.

To test the response of the transducer design of Fig. 2, two such transducers were connected face-to-face, one acting as a transmitter and one as a receiver, and the amplitude spectrum and distortion measured over the frequency range from 10 kHz to 600 kHz. The amplitude spectrum was, as desired, flat over a significant part of this range (±2.5dB from 80 kHz to more than 400 kHz -see Fig. 2) and the harmonic distortion was less than 0.6% over the frequency range from 80 kHz to 500 kHz. The transducers were thus suitable for use in the non-linear acoustic testing modes described above, and placed in suitable housings along with their drive electronics to form the transmitter and receiver modules (as also shown in Fig. 2).

3. Experimental results and discussion

The various non-linear acoustic techniques introduced in §1 above can be roughly categorised into one of two main types, namely: (1) non-linear propagation; here it is common to measure the amplitude dependency of resonant frequency, and (2) non-linear modulation; here we induce distortion or harmonic, overtone and modulation product generation due to the power law relationship between stress and strain and material hysteresis. In this paper we concentrate on the second category, non-linear modulation. We also investigate a variation of this category (one that has not been widely reported for use in assessing defects and damage in CFRP composite materials and structures), i.e. impulse response testing, where we exploit the non symmetrical response of damage/defect containing CFRP materials to compressional and tensile pulsed excitations.

3.1 Non-linear response of CFRP under tensile loading

The basic operation of the non-linear acoustic test system described above was confirmed by investigating the non-linear response of CFRP plates under tensile loading. The CFRP material was supplied by Bodycote CSM and is of the type used for structural aeronautical and aerospace applications (specifically the sample was 32 ply AS4/8552 $[0,90,-45,+45)_4]_{s32}$ laminate). For the tensile loading tests, rectangular samples of size 173 mm x 22 mm and 4 mm thick were used. These were placed in a commercial tensile loading machine (Lloyd instruments ltd LR300K) and subjected to tensile loads of 0,10, 20, 30 and 50 kN. After each load the sample was removed and various non-linear acoustic methods applied to detect sample damage; here we report results from 2nd harmonic generation and impulse inversion. The experimental arrangement is shown in Fig. 3, along with the resulting stress-strain curves (note that the sample failed at 54.5 kN, when trying to apply a load of 60 kN).

3.1.1 Harmonic generation tests

The results of 2nd harmonic generation tests are shown in Fig. 4 (the excitation frequency here was 130 kHz). Initially, for the un-loaded case, the 2nd harmonic was very weak, but, as observed by others, not entirely absent [16, 25]. After a 20 kN load had been applied the 2nd harmonic became much more obvious and after the application of a 30 kN tensile load the 2nd harmonic signal was very clearly defined (with a peak amplitude of –42 dB or 0.8%). No visual damage was evident at this stage. Interestingly, on applying a 40 kN load the sample produced an acoustic emission (AE) signal (a high frequency cracking sound) and, on removal of the load and harmonic testing a significant 3rd harmonic was evident (see Fig. 4), but again there was no visual indication of damage. The sample was then stressed above 50 kN and finally failed dramatically (snapped) at 54 kN (i.e. at a stress of ~91 MN/m^2 and a strain of ~3.4%).

It is commonly stated that the typical damage behaviour in laminated composites consists of transverse micro-cracking, followed by delamination and, eventually, fibre breakage [11]. Our results are in line with this view since, for tensile loads up to 30 kN, the dominant non-linearity is that of the 2nd harmonic and the generation of even harmonics has been shown to arise predominantly from a form of 'clapping' non-linearity consistent with the opening and closing of microcracks [16]. For higher loadings (40 kN and above) the 3rd harmonic was clearly evident, and this is consistent with the onset of delamintations; odd harmonics are expected to develop for hysteretic-type tangential movements of material 'planes' within the sample, with such movements associated with the presence of delaminations [16].

3.1.2.Pulse-inversion testing

In medical applications the benefits of the use of 2nd harmonic imaging have been known for some time, and to improve the performance of such 2nd harmonic-based approaches a pulse-inversion technique was recently developed [26]. In this 'conventional' pulse-inversion approach, two sinusoidal burst-like tones are used for imaging, each 180^0 out of phase with the other. The individual time-domain responses to these two tones are then subtracted from each other, cancelling out the linear (common-mode) signal while leaving the non-linear signal intact, hence improving the signal-to-noise ratio. While such pulse-inversion methods have received considerable attention, and application, in the medical field, their use for damage and defect detection in CFRP composite materials has to date been rather limited, although some application to crack detection in metal alloys has been reported [27, 28]. In this work, therefore, we investigate the use of the pulse-inversion method for damage detection in CFRP materials, using a simplified method based on excitation by rectangular pulses rather than tones.

To implement our simplified pulse-inversion technique, the multi-functional instrument of Fig. 1 was re-configured to deliver to the transducer (transmitter) simple rectangular excitation pulses, in this case of 1 μs duration and with a phase of either 0^0 or 180^0. One pulse induces compressional excitation, while the other induces tensile excitation; thus, we carry out a form of impulse testing. In the absence of any defects, a symmetrical stress-strain response in the CFRP material is expected, and so a summation of these compressional and tensile responses should be zero. In the presence of defects/damage however, a non-symmetrical stress-strain relationship will result and the summation will (should) be non-zero.

Pulse-inversion results taken with the experimental arrangement of Fig. 3, but in this case with transmitter and receiver placed either side of the CFRP sample (i.e. using through-transmission technique), are shown in Fig. 5 for the case of a sample that had previously been subjected to a 50 kN tensile load. The sum of the two received signals, corresponding to the 0^0 and 180^0 rectangular pulse excitations, is clearly non-zero, indicating the presence of significant non-linear effects and therefore damage (in this case, based on the results from §3.1.1, both micro-cracking and delamination would be present). By comparison, also shown in the same figure is the case for an undamaged sample (i.e. a sample not subjected to any tensile loading) where the sum of the compressional and tensile waves is effectively zero, indicating little non-linear generation. Clearly the pulse-inversion approach, which to date has received scant attention in the literature for applications to damage and defect detection in CFRP materials and structures, is a very effective technique and, significantly, is particularly simple and straightforward to implement, requiring very little post-processing of the received signal compared to more 'conventional' non-linear acoustic approaches.

While the demonstration of the generation and detection, using our multi-functional approach, of non-linear acoustic effects in CFRP samples subject to damage induced by tensile loading is very informative, a practicable system must also be able to detect damage more commonly induced in CFRP materials and structures by 'everyday use'. In the following sections, therefore, we apply the techniques of harmonic generation and pulse-inversion for the detection of both impact-induced and heat-induced damage, both important damage routes for modern, composite, aerospace materials and structures.

3.2 Detection of impact-induced damage and degradation

It is well known that the mechanical properties, such as the compression strength, of composite materials can be significantly reduced by even low-level impacts, for example by the dropping of tools onto structures during maintenance, and that such low-level impact damage is often not detectable by visual inspection. Conventional (linear) ultrasonic techniques such as C-scans can be quite effective in detecting such impact damage and have revealed that impact-induced damage in CFRP laminates is principally manifested in the form of delaminations [8] and cracking [2]. Non-linear techniques are also very sensitive to delamination and cracking, since such defects produce strong contact-mediated acoustic non-linearity [16].

A simple but effective way of revealing impact-induced contact-mediated non-linearity is via the harmonic generation. Thus, the instrument of Fig. 1 was configured for harmonic generation operation and a series of impact tests on a CFRP composite plate carried out. The sample was a CFRP plate (375 mm x 300 mm x 4 mm in size) of the same type as used in §3.1 above. A commercial drop-weight impact-tester was used to subject the plate to various impact loadings, ranging in energy from 4 J to 69 J and over an impact radius of 6.25 mm. A 130 kHz interrogating sinusoidal tone was amplified and fed to a (transmitter) transducer of the type shown in Fig. 2, while a similar transducer acted as a receiver (the transmitter and receiver were placed either side of the impact site, each 35 mm from the centre of the impact). The 'smart control' module shown in Fig. 1 was programmed to capture 10^7 samples per second from the receiver, via the 12 bit A/D converter. Samples were then transferred to the laptop PC, a FFT (Fast Fourier Transform) performed to find the received signal spectrum and the amplitude of any higher order harmonics (i.e. 2nd harmonic at 260 kHz, 3rd harmonic at 390 kHz etc.) calculated in software.

Impact testing results are shown in Fig. 6, where it can be seen that the 2nd harmonic amplitude increases essentially monotonically with impact energy, reaching a maximum of 8% (of the fundamental harmonic amplitude) for the maximum impact energy of 69 J. The 3rd harmonic shows and increase to around 4% at 29 J, thereafter it reduces again, whereas the level of the 4th harmonic is relatively flat as a function of impact energy. These results can be understood in terms impact damage mechanisms reported in the literature, with a typical damage morphology consisting of micro and macrocracking running through laminate layers and delamination between the layers of the laminate, with size of delaminated regions increasing markedly with impact energy [2,8]. Thus, we would expect the amplitude of the second harmonic to increase monotonically with increasing impact energy as the severity (number and size) of the through-laminate cracks increases, as indeed observed. It would also be expected that the 3rd harmonic would increase in size as delaminations form with increasing impact energy, leading (as in the tensile loading tests reported in §3.1.1) to the onset of hysteretic-type tangential movements of material 'planes' within the sample that are known to generate odd harmonics [16]. The eventual decrease in 3rd harmonic amplitudes is, we believe, due to the increasing diameter and width (opening) of the delaminations at high impact energies leading to reduced hysteretic tangential movement.

Clearly, harmonic generation is very effective in this case as an indicator of impact-induced damage, with, as evident from Fig. 6, the total harmonic distortion (THD) being particularly useful at relatively low impact energies where visual evidence of damage is lacking (here samples showed no visible damage for impact energies below 30 J) but where significant deterioration of compressive strength is known to occur [8].

3.3 Detection of thermally-induced damage and degradation

Modern engineering composites can also suffer from significant thermally-induced damage and degradation. For example, in aircraft and aerospace applications parts made from composite materials might be exposed to damaging levels of heat as a result of fire, lightning strikes, jet engine exhaust, exposure to hot gases from missile efflux or the ground reflected engine efflux from vertical or short-takeoff and landing aircraft, etc.. Furthermore, modern turbine engines themselves contain significant amounts of composite materials. Indeed, aircraft engines have today evolved to include so many major composite components that CFRP-based composites, often combined with honeycomb structures (such as Nomex® or HexWeb® honeycombs), account for around half the volume of the entire engine nacelle structure, with such nacelle structures and materials being exposed to elevated temperatures for extended periods.

Clearly, there is a pressing need for reliable methods for the detection of thermally-induced damage or degradation in composite materials. As in the case of impact-induced damage, thermally-induced damage may not be evident from simple visual inspection and it may not be feasible or desirable to remove parts for laboratory inspection and/or destructive-type tests. Thus, a non-destructive, and ideally in-situ, method for detecting thermally-induced damage is highly desirable. Previous work indicated that mechanical properties change well before the microstructural alterations can be detected with classical, linear, ultrasonic techniques [29, 30]. Indeed, in some cases[20 22], the signal attenuation in linear acoustic studies was shown to decrease with thermal loading (of CFRP samples), whereas it might be expected that such attenuation would increase due to increasing damage (it was proposed by the authors of [20 22] that increased acoustic attenuation due to damage was masked by changes in the linear properties of the composite matrix, e.g. heat-induced chemical and molecular changes in the resin). On the other hand, a non-linear (resonance-type) ultrasonic technique was successful in detecting thermal damage in various commercial CFRP laminates subjected to temperatures in the range 200^0C to 300^0C for between 15 and 60 minutes duration [19, 22]; resonance properties were shown to change with thermal loading and such changes were highly correlated with the presence of thermally-induced delaminations. Wolfrum et al. also showed micro-cracking and delamination in 8552/IM7 aerospace composite laminates thermally annealed at 200C [30], noting a loss of mechanical strength, changes in fracture behaviour, mass loss and a thermo-oxidative degradation of the matrix resin. However, Wolfrum et al. used a combination of destructive testing (e.g. fracture testing and microscopic cross-sectional analysis) and chemical analysis (e.g. infra-red spectroscopy), rather than ultrasonic-based approaches. Krohn et al. [16] reported 2nd harmonic generation in CFRP samples subjected to laser heating to simulate a thermal overload, but did not include any temperature measurement and with the amplitude of the 2nd harmonic being determined indirectly by laser vibrometry, rather than directly using piezoelectric sensor (as in this work).

Here, we use the multi-functional instrumentation described in §2 above to detect thermally-induced damage in a CFRP-Nomex® honeycomb composite structure, as typically used commercially for engine nacelle, aeroplane wing and helicopter rotor applications. Specifically the sample here consisted of a section of helicopter rotor having a Nomex® thickness (at the location tested) of 50 mm and bonded top and bottom to a CFRP laminate of 1.5 mm thickness. The sample was heated locally on one side and the temperature measured by a radiation pyrometer. Various temperatures in the range 100^0C to 200^0C were applied for various durations and the non-linear acoustic (specifically here harmonic generation and pulse inversion) testing carried out once the sample had cooled back down to room temperature (transmitting and receiving transducers were placed 50 mm apart, either side of the heated area). It is important to note that for all except the highest thermal loadings used there was no visual evidence of damage or degradation to either the CFRP plates or the Nomex® honeycomb; however, as we show below, very significant changes occurred in the non-linear acoustic properties.

In Fig. 7(a) we show the acoustic spectrum for the pristine (un-heated) CFRP-Nomex®-CFRP sample. An excitation frequency of 50 kHz was used in this case, the peak value of the received signal was 433 mV and the spectrum comprised mainly the fundamental frequency, with very little evidence of higher harmonics. However, as shown in Fig. 7(b), after raising the surface temperature of the sample surface to 200^0C and maintaining this temperature for 3 minutes, very considerable harmonic generation is evident, with the 2nd harmonic level exceeding 6% of the fundamental and a small (1%) 3rd harmonic also being visible. Indeed, the 2nd harmonic amplitude increased monotonically and substantially with increasing thermal load, as shown in Fig. 7(c). Visual and cross-sectional inspection of the sample after application of the 200^0C/3 minute thermal load revealed evidence of blistering, voids and cracks in the top (i.e. the heated) CFRP plate, with such damage no doubt responsible for the observed increase in the 2nd harmonic signal with thermal load (again, such types of damage would be expected to lead to 'clapping' like non-linearities known to generate even harmonics [16]). The small 3rd harmonic at high thermal loads may indicate the onset of disbonding at the CFRP/honeycomb interface.

The very significant non-linear contributions manifested in the spectra of Fig. 7 are also expected to lead to very different pulse-inversion responses, pre and post thermal treatment. This was indeed the case, as seen in Fig. 8(a) and Fig. 8(b), where the responses to excitation by a 'positive' pulse (comprising a +40 V amplitude held for 10 μs then -40 V held for a further 10 μs) and an opposite 'negative' pulse (comprising a -40 V amplitude held for 10 μs then +40 V held for a further 10 μs) are shown. For the sample heated to 200^0C the difference between the response for the 'positive' and 'negative' pulses are very significant, unlike the case for the undamaged (pristine) sample.

Clearly both the harmonic generation method and the pulse-inversion method are very sensitive in their ability to detect heat-induced damage, at least in the CFRP-honeycomb structure detailed here. Again, the simple pulse-inversion approach, which requires no (relatively) complicated signal post-processing (such as FFT calculation), is seen to provide a very effective method to identify damage, in this case voiding and cracking due to thermal loading. In fact, we have also performed similar non-linear tests on a range of commercial nacelle type CFRP structures, and found non-linear techniques to be extremely good at detecting thermal damage induced in real practical applications.

4. Conclusions

Various non-linear methods have been investigated in recent years for the detection of faults and fatigue in carbon-fibre reinforced composite materials and structures. However, there is no universally-agreed rationale for which technique is best suited to the detection of which type of defect. Furthermore, even if such a rationale were to exist, real-world samples potentially contain a variety of defects (e.g. micro-cracking, delamination and disbonding) induced by various damage mechanisms (stress, impact, heat) such that no single non-linear testing technique can offer the optimum inspection choice in all circumstances. We have therefore developed a multi-functional, non-linear detection approach using programmable and re-configurable instrumentation that not only includes all the main non-linear ultrasonic testing regimes, but also incorporates a pulse-inversion technique which has so far been largely un-reported in the literature in terms of damage and defect detection in CFRP materials and structures. We demonstrated the capabilities of this new multi-functional instrumentation for defect detection by examining various CFRP samples, specifically CFRP laminates used as wing material in fighter aircraft and CFRP- Nomex® honeycomb structures used in helicopter rotor blades, subjected specifically stress-induced, impact-induced and heat-induced damage. We showed that the multi-functional non-linear approach is well-suited to the detection of such forms of damage and that the pulse-inversion technique in particular is potentially a powerful, but as yet un-tapped, simple and effective route to the defect and damage detection.

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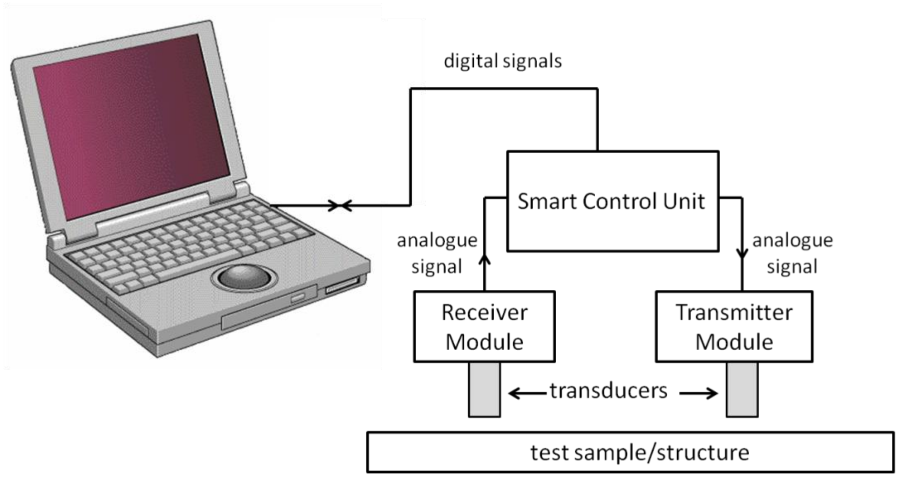

Fig. 1. Basic configuration of the multi-functional, non-linear, ultrasonic instrumentation

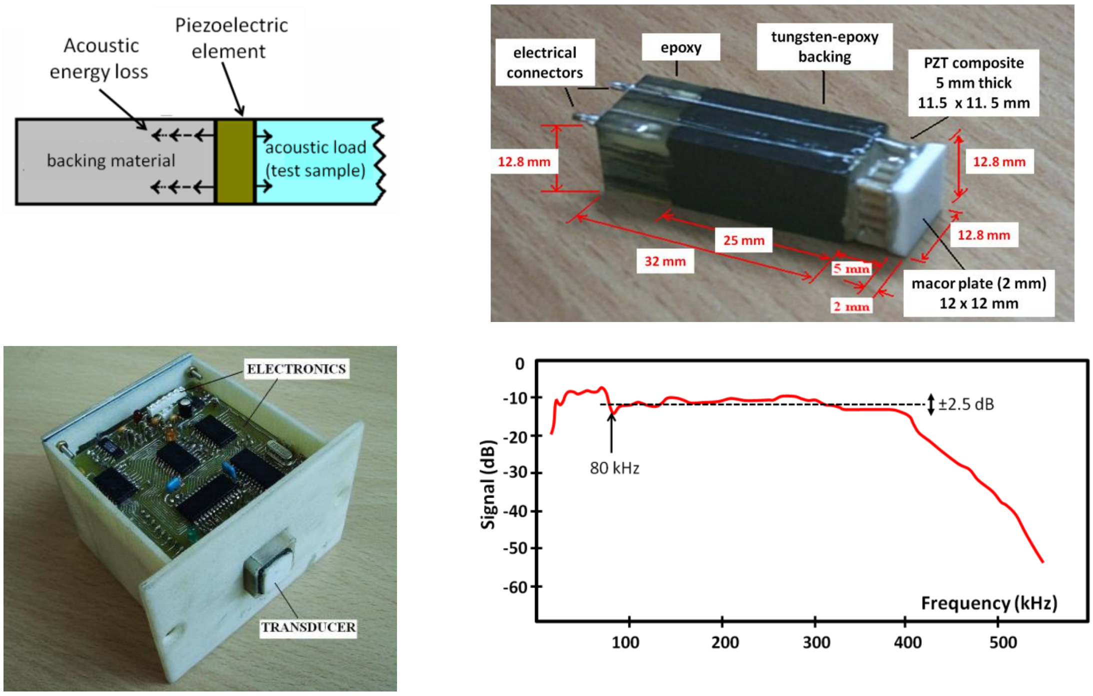

Fig. 2. (top) Basic design of wideband ultrasonic transducer and photograph of actual transducer fabricated and (bottom) photograph of transducer mounted in its housing along with associated drive/receive electronics and frequency response of coupled transmitter/receiver pair.

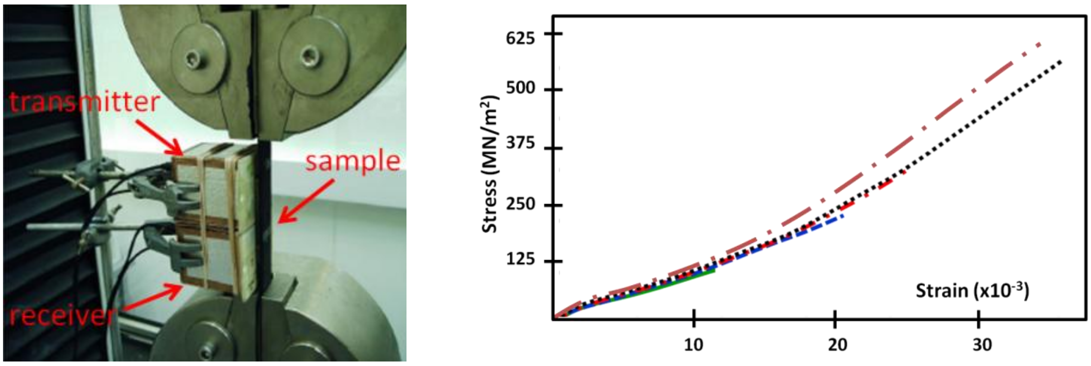

Fig. 3. Tensile testing arrangement (left) and resulting stress-strain responses (right) for maximum applied loads of 10, 20, 30, 50 kN and the breaking load of 54 kN.

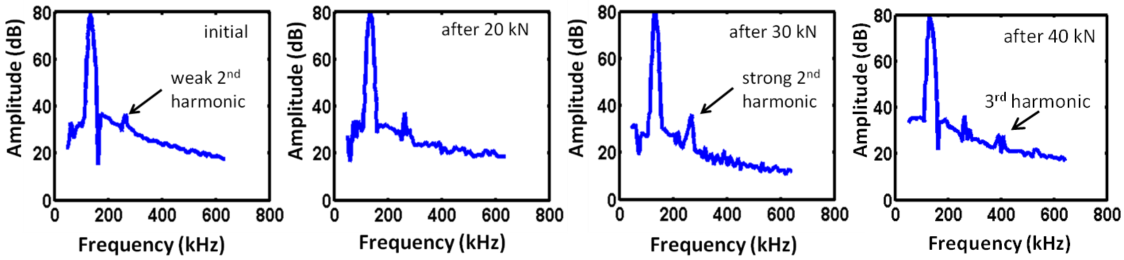

Fig. 4. Spectrum of the received acoustic signal for CFRP sample subjected to tensile loading: no load case (left) and after 20 kN, 30 kN and 40 kN had been applied.

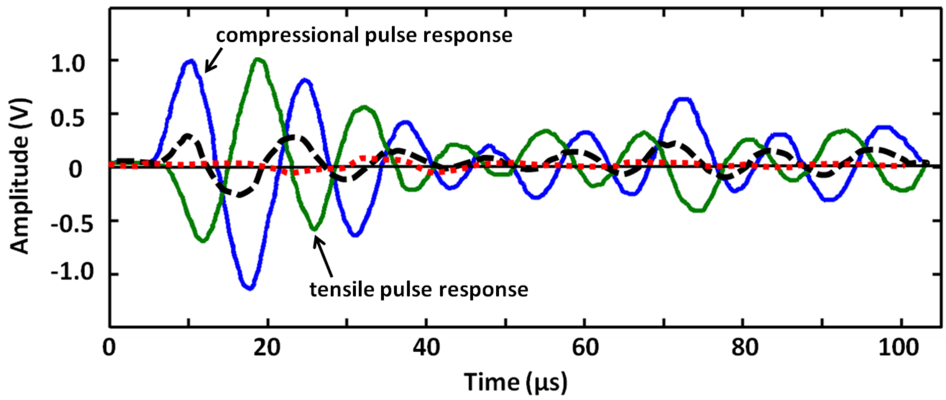

Fig. 5. Results of pulse-inversion testing showing the response of a (previously 50 kN loaded) CFRP sample to compressional and tensile pulse excitations and (dashed line) the sum (divided by two) of the two responses. Also shown (dotted line) is the summed response for an un-loaded (i.e. pristine) sample.

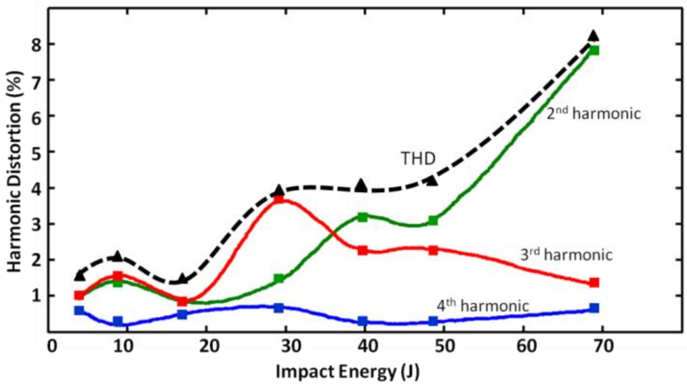

Fig. 6. Amplitude (as a percentage of fundamental) of the 2nd, 3rd and 4th harmonics as a function of impact energy for CFRP sample. Also shown (dashed line) is the level of total harmonic distortion.

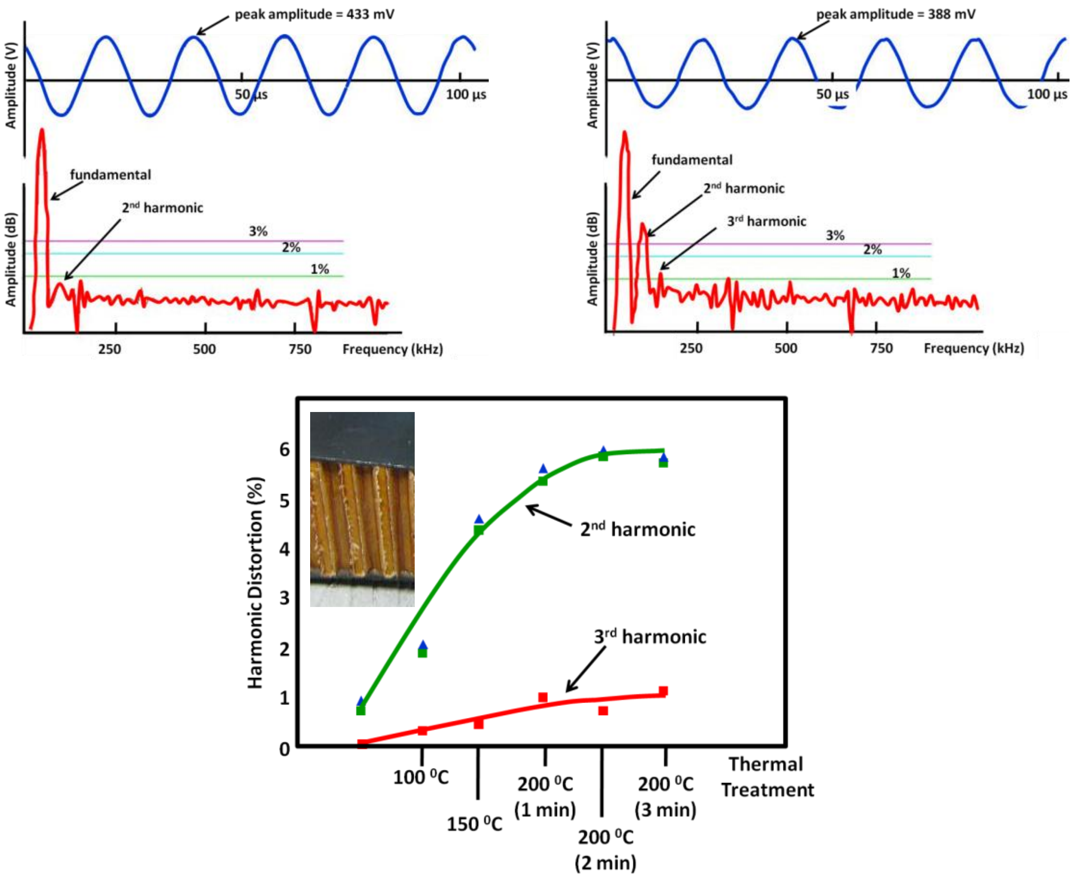

Fig. 7. (a) Received signal and spectrum for un-heated CFRP/honeycomb sample (top left); (b) signal and spectrum for same sample locally heated to 200^0C for 3 minutes (top right); (c) amplitude (as a percentage of fundamental) of the 2nd and 3rd harmonics for various thermal loads. Also shown in (c) is the total harmonic distortion (triangles) and (inset) a photograph of a cross-section of the CFRP-Nomex® honeycomb composite structure.

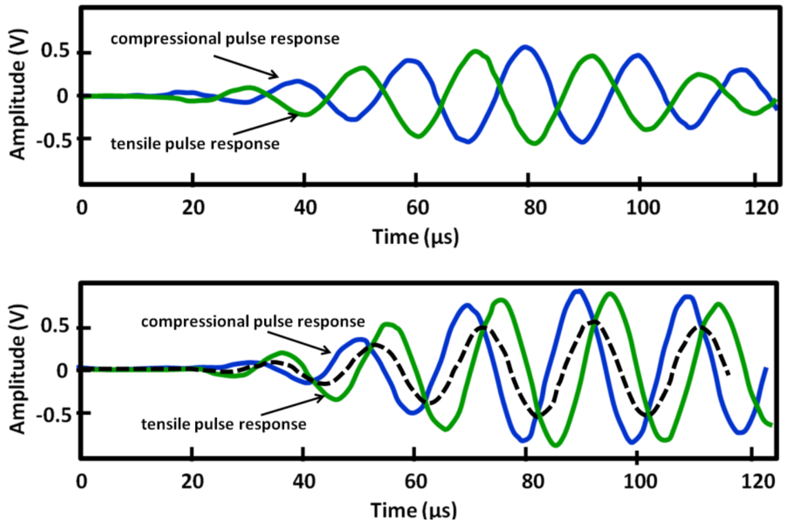

Fig. 8. Pulse inversion responses for (a) un-heated CFRP/honeycomb sample (top) and (b) for same sample locally heated to 200^0C for 3 minutes (bottom). Also shown (dotted line in (b)) is the summed response (divided by two) for the thermally-damaged sample.