Ultrasonic resonance of defects for nonlinear acoustic imaging and NDT

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Abstract
The effect of local defect resonance (LDR) on the nonlinear ultrasonic response of defects is studied and applied for enhancement of sensitivity of nonlinear ultrasonic NDT. As the local vibration amplitude increases, the LDR-“amplifier” exhibits transition to nonlinear regime with an efficient generation of nonlinear frequency components solely in the defect area. The concept of the defect as a nonlinear oscillator brings about different dynamic and frequency scenarios characteristic of parametric oscillations. The experiments confirm unconventional nonlinear dynamics of simulated and realistic defects subject to LDR. The nonlinear modes observed include sub- and superharmonic resonances with anomalously efficient generation of the higher harmonics and subharmonics. A modified version of the superharmonic resonance (combination frequency resonance) is used to enhance the efficiency of frequency mixing mode of nonlinear NDT. A strong localization of the resonance nonlinearity is applied for high-contrast imaging of defects in composite materials.

Keywords: Local defect resonance (LDR), defect imaging, subharmonic resonance, superharmonic resonance.

1. Introduction

The majority of acoustic NDT instruments widely used in industry and technology for material characterization and quality assessment make use of a linear elastic response of materials that generally results in the amplitude and phase variations of the input signal. The nonlinear approach to ultrasonic NDT is concerned with nonlinear material response, which is inherently related to the frequency changes of the input signal (e.g. higher harmonics (HH)). For propagating ultrasonic waves, the effects of nonlinearity manifest at moderately high input power (intensity ~ 1 W/cm^2) when a local material stiffness becomes dependent on the wave amplitude (material nonlinearity). However, this type of nonlinearity turned out to be rather inefficient: for all homogeneous and free from defects materials, the stiffness variation is usually below 10^{-3} even for high ultrasonic strains $\approx 10^{-4}$, As a result, noticeable nonlinear effects are developed only due to accumulation of the nonlinear response along the propagation distance, and, in practical terms, only the second harmonic signal can be used for material characterization and NDT.

A substantial increase in nonlinearity was found in materials with imperfections and cracked defects: an important role in this enhancement is played by internal boundaries of the defects, which provide constraints for contact vibrations. A local stiffness changes due to intermittent contact between the fragments of the defect and thus causes nonlinearity of local “bimodular” vibrations (Contact Acoustic Nonlinearity (CAN)) [1]. The CAN mechanisms are concerned with “clapping” of crack planes (for vibrations normal to the interface) and nonlinear friction between the crack surfaces for tangential vibrations. Due to CAN, the spectrum of vibrations acquires multiple higher harmonics which are nonlinear NDT signatures of the cracked defects readily observable in experiments. Besides the much higher efficiency, CAN was shown to exhibit a substantial qualitative departure from fundamental nonlinear effects of the higher harmonic generation. The family of “NDT tags” observed for nonlinear defects included frequency down-conversion (subharmonics), hysteresis, instabilities, chaotic dynamics, etc. [2].

To interpret such “unconventional” effects an assumption that the damaged area can be identified as a nonlinear oscillator (or a set of coupled nonlinear oscillators) and therefore can exhibit both nonlinear and resonance properties have been made [3]. A direct experimental proof for “resonant” defects has been obtained recently [4] and the concept of Local Defect

Resonance (LDR) introduced. The study of linear LDR properties [5] demonstrated its high spectral sensitivity in detecting and imaging of a certain defect among a multitude of other defects in materials (Linear Resonant Ultrasonic Spectroscopy of Defects (RUSOD)).

In this paper, we study the effect of local defect resonance (LDR) on nonlinear ultrasonic responses of defects. Unlike the resonance of the whole specimen, the LDR naturally provides an efficient energy pumping from the wave directly to the defect. As the local vibration amplitude increases, the LDR-“amplifier” exhibits transition to nonlinear regime with an efficient generation of the nonlinear frequency components in the defects area. In addition, the concept of the defect as a nonlinear oscillator brings about qualitatively different dynamic and frequency scenarios of nonlinear behaviour characteristic of nonlinear and parametric oscillations. It is experimentally shown that the frequency- and spatially-selective ultrasonic activation of defects by using the concept of LDR is the way to optimize efficiency of nonlinear ultrasonic NDT and imaging.

2. Enhancement of nonlinearity via LDR

2.1 Higher harmonic LDR mode

Since LDR is as an efficient resonant “amplifier” of the local vibrations, one would expect it to contribute appreciably to material nonlinearity. To begin with the study of LDR effect on nonlinearity, a circular FBH defect (thickness 0.8 mm; radius 1 cm) in a typical low-nonlinear material PMMA with the LDR frequency response at 11 kHz was measured. A scanning laser vibrometer in particle velocity mode was used to monitor the LDR vibration pattern, waveform and the spectrum including HH.

The experimental results in Fig. 1, a show that even such “linear” defects, like FBH in PMMA, turn into strongly nonlinear provided the driving frequency matches the LDR (11 kHz). For realistic defects, the higher background nonlinearity (CAN) combined with LDR results in an extremely efficient HH generation (Fig. 2). A crucial role of the driving frequency match to LDR for nonlinearity increase is illustrated in Figs. 3 and 4, correspondingly, for a delamination in glass fibre-reinforced (GFRP) plate and a crack in a unidirectional (UD-) CFRP rod. As the driving frequency matches the LDR frequencies, a strong enhancement ~20-40 dB of the HH amplitudes generated locally in the defect area is observed (Figs. 3, 4).

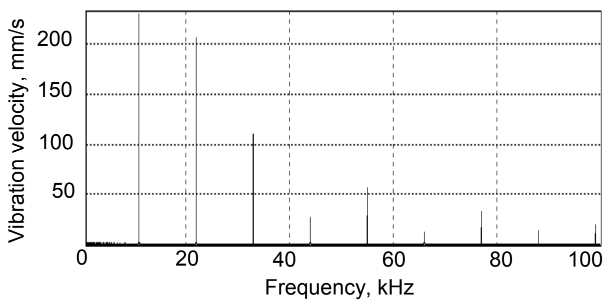

Figure 1. HH spectra of FBH in PMMA specimen driven at LDR frequency 11 kHz.

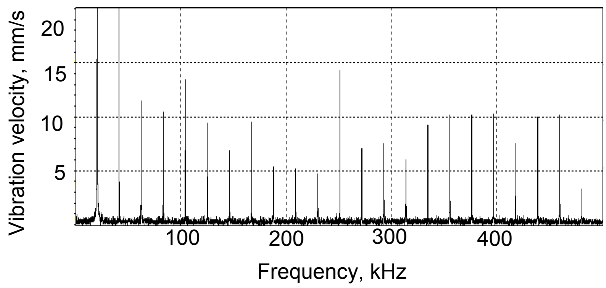

Figure 2. HH spectrum for delamination in glass fiber reinforced (GFRP) specimen driven at LDR frequency 20900 Hz. Input voltage is 7V.

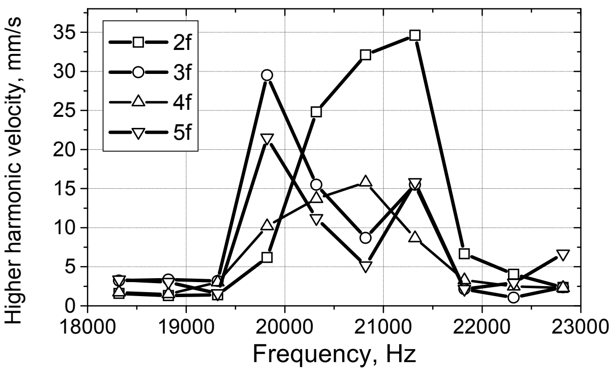

Figure 3. Higher harmonic LDR frequency responses of a delamination in GFRP plate (LDR 20900 Hz).

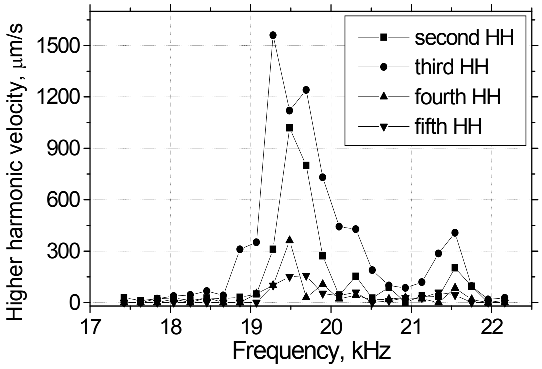

Figure 4. Higher harmonic LDR frequency responses of a crack in UD-CFRP rod (LDR 19.5 kHz).

2.2 Mixing frequency LDR mode

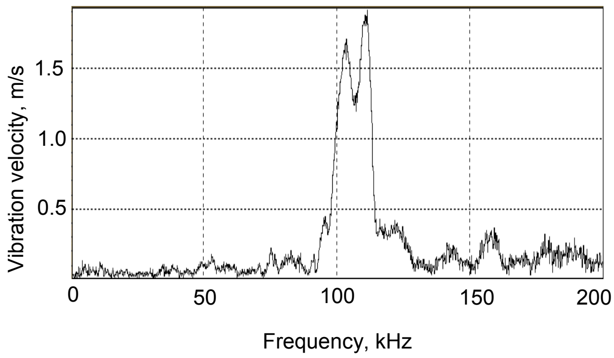

Figure 5. LDR frequency response for an impact induced damage in a CFRP plate.

The frequency mixing mode makes use of nonlinear interaction between two ultrasonic waves; it is characterized by a lower spurious signal level than the HH mode and thus is prospective for NDT applications. A high quality factor of LDR can also be used as a "linear" filter/amplifier in the frequency mixing nonlinear NDE. This method is based on the nonlinear interaction of ultrasonic waves of different frequencies (f_1, f_2) that results in a combination frequency output: $f_{\pm} = f_1 \pm f_2$. For nonlinear experiments in "classical" materials, the efficiency of interaction is highly critical to the geometry of the wave propagation and is generally rather low: the amplitude ratio $U_{\pm}/U_{1,2}$ is normally below $10^{-3} - 10^{-2}$. A high-Q LDR can be used to enhance the output signal by a combination frequency (or any of the interacting frequencies) match to the LDR frequency response. This approach will be applicable to any geometry of the wave interaction since LDR response is weakly sensitive to its position in the wave field.

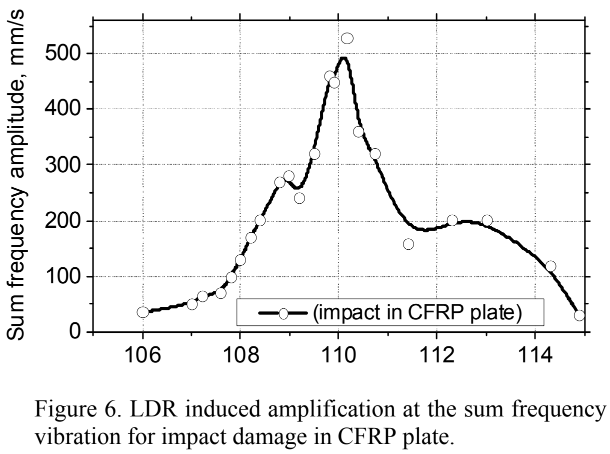

Figure 6. LDR induced amplification at the sum frequency vibration for impact damage in CFRP plate.

An application of LDR as the "frequency mixing amplifier" for NDE and imaging of realistic defects is illustrated then in Figs. 5 & 6 for an impact-induced damage (area ~5x5 mm^2) in the CFRP plate (280x40x1 mm^3). A linear LDR frequency response of the impact demonstrates a well-defined double-maxima peak around 110 kHz (Fig. 5). In the experiment, the two interacting flexural waves were excited in a continuous wave mode by the piezo-transducers attached to the opposite edges of the plate. One of the frequencies was fixed at $f_1 = 77.5$ kHz while the other was swept from $f_2 = 28.5$ to 37.5 kHz to provide the sum frequency variation around the LDR frequency of the defect. The vibration velocity amplitudes at f_1, f_2 and f_+ were monitored in the centre of FBH with a laser scanning vibrometer (vibration velocity mode). Fig. 6 shows the normalized velocity amplitude at sum frequency as a function of f_+ measured by changing f_2 in the frequency range indicated above. The impact of LDR is clearly seen by comparing the data with those in Fig. 5: more than 20 dB increase in the output is observed when the combination frequency matches the frequency of LDR.

3. Parametric nonlinearity of resonant defects

According to the above, at moderate input signals the LDR enhances appreciably the nonlinearity of defects via local "amplification" of vibrations. It raises substantially the efficiency of "conventional" nonlinear effects, like HH generation and wave mixing. However, this is not the only dynamic scenario of nonlinear phenomena for resonant defects. At higher level of excitation, a combined effect of LDR and nonlinearity can result in qualitatively new features characteristic of the nonlinear and parametric resonances.

The former is concerned with resonance generation of the higher harmonics (superharmonic resonances) and subharmonics (subharmonic resonances). For the superharmonic resonance, the input frequency is taken as $\approx \omega_0 / n$ and converted into ω_0 drive via the nth-order nonlinearity of the oscillator.

Manifestation of parametric effects (resonant growth of super- and subharmonic vibrations) is due to the amplitude-dependent shift (modulation) of LDR frequency induced by the driving signal. Unlike conventional (linear) resonance, the parametric resonances provide an exponential growth of the vibration amplitudes in time even in the presence of damping. Such instability develops as soon as the frequency modulation index (input signal amplitude) exceeds a certain threshold determined by the energy dissipated in the system.

3.1 Experimental

The experimental data given below demonstrate that the nonlinear resonance and parametric dynamics should be seen not as exceptional or anomalous but rather conventional and peculiar to majority of defects in the resonance conditions. The measurements in Fig. 7 show that the unstable nonlinear dynamics is observed for an impact damage (LDR at 5140 Hz) in CFRP sample. As the driving amplitude increases, the vibration of the defect at 5140 Hz LDR remains monochromatic until the threshold input ~30V (Fig. 7). The switchover to nonlinear regime with efficient HH generation takes place at the input ≥ 30 V: in this range the output signals are unstable with frequent "jumps" of the amplitude measured. Beyond the threshold, the instability ceases and the vibration returns to stability heavily distorted with a decrease of the resonance response at the fundamental frequency (Fig. 7).

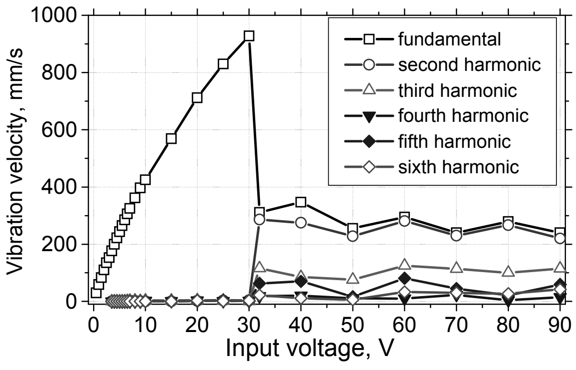

Figure 7. Bifurcation nonlinear dynamics for LDR in CFRP plate.

This behaviour is in accord with general analysis given above for parametric resonances: the input at LDR frequency beyond the threshold provides an instable growth of the HH. The fundamental vibration is depleted due to energy outflow and heavily distorted via frequency conversion to HH.

A direct proof of superharmonic resonances in defects is demonstrated for the same CFRP specimen with LDR around 5140 Hz in Fig. 8. A one-half driving frequency (2570 Hz) was therefore selected for the excitation. To overcome parametric threshold, the input voltage was increased up to 60 -70 V. The spectrum (Fig. 8, a)) and the vibration pattern (Fig. 8, b) measured in the defect area beyond the threshold (65 V input) illustrate the dominance of the second harmonic vibration (period ~0.19 ms in Fig. 8, b)). Because of the high-Q fundamental LDR, the superharmonic resonance required quite precise half-frequency placing within (10-20) Hz.

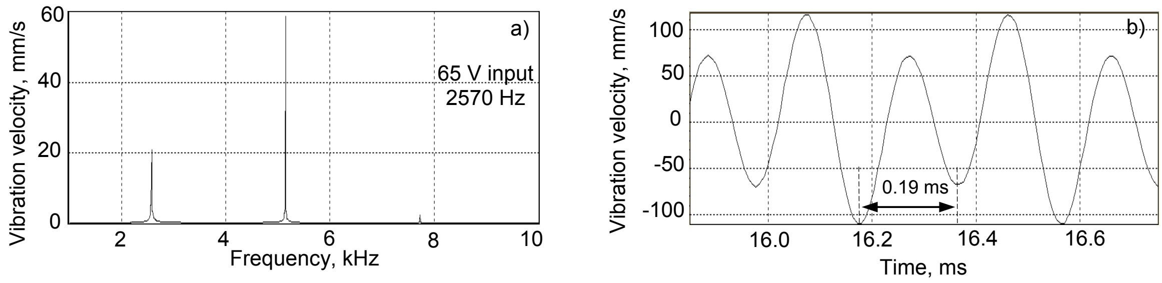

Figure 8. Second-order superharmonic LDR for impact damage in CFRP: spectrum (a); vibration pattern (b).

The excitation frequency was then changed to the second harmonic (10280 Hz) frequency range of the fundamental LDR to observe a subharmonic resonance. The threshold for the resonance was found to be ≈ 45 V. Beyond the threshold, the subharmonic component increases dramatically and prevails in the vibration (velocity) spectrum: $V_{\omega/2} / V_{\omega} \approx 30$ dB at 10275 Hz input (Fig. 9, a)). This complies with pure sinusoidal subharmonic vibration pattern in the impact area beyond the threshold input (Fig. 9, b)). The input frequency range for the subharmonic LDR was measured to be ~ 200 Hz, i.e. somewhat wider than that for the superharmonic counterpart.

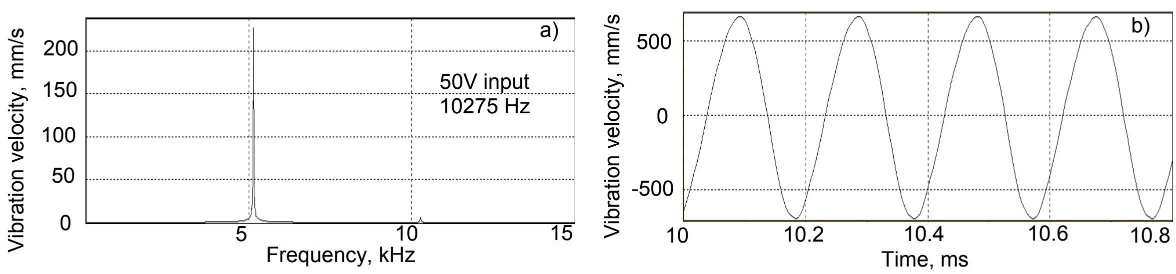

Figure. 9. Subharmonic LDR for impact damage in CFRP: spectrum (a) and vibration patterns (b).

The use of nonlinear LDR thus enables to amplify dramatically nonlinear response of defects. This suggests nonlinear LDR application as an efficient mode in nonlinear NDT. Besides, both super- and subharmonic LDR are strongly localized in the defect area that provides a background for the high-contrast defect-selective imaging.

4. LDR defect-selective imaging

A local “amplification” of vibrations is a basis of a sensitive frequency-selective imaging even in a linear LDR case. The benefit of the linear LDR imaging is demonstrated in Fig. 10, where it is used for visualization of two small square artificial delaminations (8x8 mm^2 and 12x12 mm^2) with LDR frequencies 91130 Hz and 71250 Hz, correspondingly, in a CFRP plate (300x300x3 mm^3). The excitation at corresponding LDR frequencies results in imaging of the defects separately (Fig. 10 a, b) while a frequency sweep within the frequency range of both LDR brings a clear image of the both defects (Fig. 10, c).

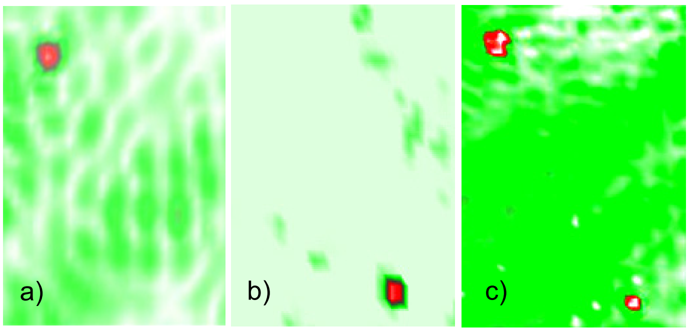

Figure. 10. Frequency-selective defect imaging of delaminations in CFRP plate in a linear LDR mode: excitation frequency 71250 Hz (a); 91130 Hz (b); frequency sweep 45-100 Hz (c).

By combining the resonance conditions provided by LDR with highly efficient elastic non-linearity (CAN) a substantial improvement in detecting and imaging of realistic defects can be expected. The benefit of the higher harmonic LDR imaging is illustrated in Fig. 11 & 12. A substantial improvement of the image quality was observed for the second harmonic LDR of 10x20 mm^2 delamination in 1 mm GFRP plate: the signal-to-noise ratio (SNR) of the non-linear image in Fig. 11, b) is ~24 dB, while ~12 dB was measured at 36.77 kHz for the fundamental frequency LDR (b). A similar enhancement in non-linear image quality is readily seen by comparing the linear LDR (3.67 kHz) (Fig. 12, a)) and the second harmonic images (Fig. 12, b)) of impact-induced fibre loss damage in CFRP plate.

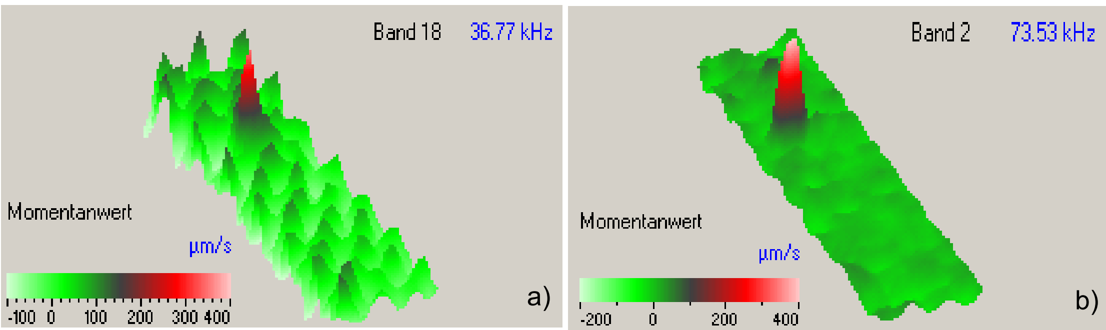

Figure 11. LDR nonlinear imaging of defects: fundamental and the second harmonic LDR images of ~ 10x20 mm^2 delamination in GFRP plate.

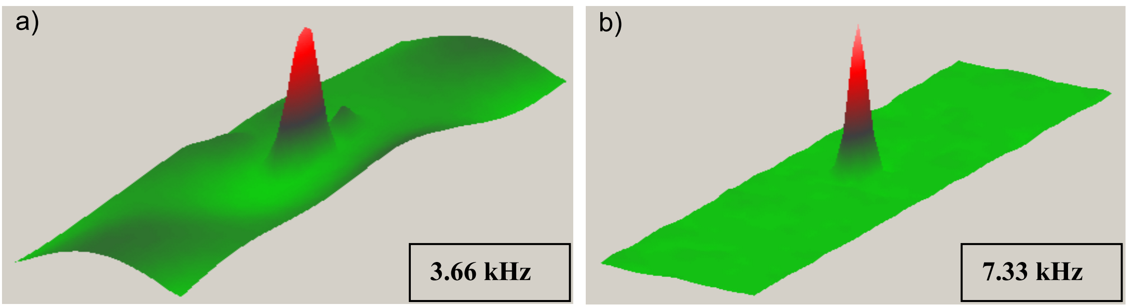

Figure 12. LDR nonlinear imaging of defects: fundamental and the second harmonic LDR images of impact induced fibre loss in CFRP plate.

The LDR contribution to the sum-frequency signal (see Section 2) makes it localised in the damage area and enables it to be used for mixing frequency imaging with reasonable signal-to-noise level (~15 dB, Fig. 13). This image of the impact in CFRP plate was obtained by mixing two flexural waves of frequencies 77 kHz and 30 kHz via the combination frequency resonance (LDR frequency of the defect 107 kHz).

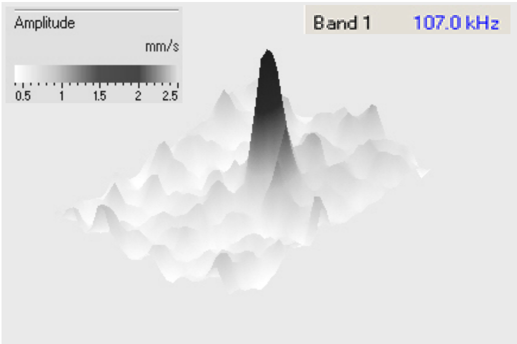

Figure 13. Sum-frequency image of the impact-induced damage (~5x5mm^2) in a CFRP plate.

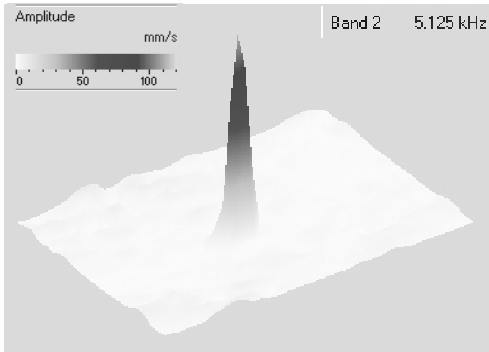

Figure 14. Subharmonic LDR imaging of impact damage in a CFRP plate: Input 10250 Hz; output 5125 Hz.

Other examples of the resonance nonlinear imaging are given in Figs. 14 & 15. Fig. 14 uses a subharmonic resonance for imaging of an impact damage in CFRP: the specimen is excited at 10275 Hz and the subharmonic image is visualized at LDR frequency 5140 Hz. A drastic increase of the signal-to-noise ratio due to nonlinear resonance is readily seen from Fig. 15 for the third-order superhamonic resonance in the same impact damaged CFRP specimen: the excitation frequency at one third of the LDR frequency obviously does not match resonance conditions (a) while the third harmonic does and results in ~17 dB SNR.

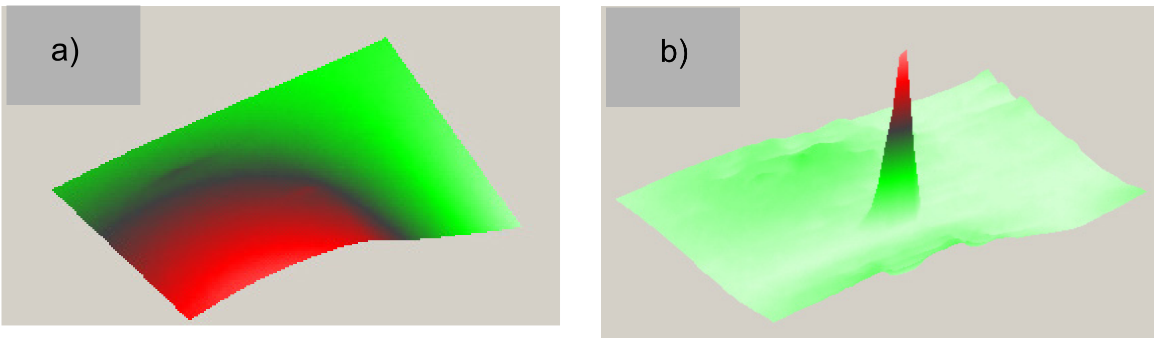

Figure 15. Third-order superharmonic imaging of impact damage in CFRP: fundamental frequency (1715 Hz) image (a), the third HH (5145 Hz) image (b).

5. Conclusions

The bottleneck problem of nonlinear NDT is a low efficiency of conversion from fundamental frequency to nonlinear frequency components. In this paper, it is proposed to use a combination of nonlinearity with Local Defect Resonance to enhance substantially the input-output conversion.

Since LDR is an efficient resonance “amplifier” of the local vibrations, it manifests a profound nonlinearity even at moderate ultrasonic excitation level. As the driving frequency matches the LDR-frequency band, a strong enhancement (up to 40 dB) of the HH amplitudes generated locally in the defect area is observed. Besides a strong higher harmonic response, a high quality factor of LDR can also be used as a filter/amplifier in the frequency mixing nonlinear NDE.

The "conventional" nonlinear effects, like HH generation and wave mixing are not the only dynamic scenario of nonlinear phenomena for resonant defects. At higher level of excitation, a combined effect of LDR and nonlinearity results in qualitatively new features characteristic of nonlinear and parametric resonances. Manifestation of parametric effects (resonant growth of super- and subharmonic vibrations) is due to the amplitude-dependent shift (modulation) of LDR frequency induced by the driving signal.

Under resonance conditions nearly total input energy at fundamental frequency can be converted into HH or subharmonic vibrations of the defects. This suggests nonlinear LDR application as an efficient mode in nonlinear NDT. Both super- and subharmonic LDR are strongly localised in the defect area that provides a background for high-contrast defect- and frequency-selective imaging.

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