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Highly-Sensitive Defect-Selective Imaging and NDT via Resonant Nonlinearity of Defects

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Abstract

In this paper, it is proposed to use a combination of mechanical resonance and nonlinearity of defects to enhance substantially the efficiency of input-output frequency conversion in nonlinear NDT. The concept of a defect as a nonlinear oscillator brings about new dynamic and frequency scenarios characteristic of nonlinear and parametric oscillations. The experiments confirm transition to resonant modes of nonlinear vibrations in simulated and realistic defects. All resonant nonlinear modes are strongly localised in the defect area that provides a background for high-contrast highly-sensitive defect- and frequency-selective imaging.

Keywords: local defect resonance, superharmonic and subharmonic resonances, nonlinear ultrasonic imaging.

1. Introduction

In flawless materials, acoustic nonlinearity is associated with lattice anharmonicity and reveals nonlinear behaviour of inter-molecular forces. It implies that the stiffness of a nonlinear material is, in principle, a function of strain that leads to a local variation of the wave velocity, waveform distortion and higher harmonic (HH) generation. However, the measurements showed that even for high ultrasonic strains in free from defects materials, the amplitude dependent stiffness variation is extremely low. As a result, noticeable nonlinear effects are developed only due to accumulation of the nonlinearity along the propagation distance (in the lack of dispersion), and, in practical terms, solely the second harmonic signal can be used for material characterization and NDT.

Even in the first experimental studies a substantial increase in nonlinearity was noticed in materials with imperfections: a substantial enhancement of the second harmonic signal was measured for a dislocation field induced in metal by mechanical stress applied [1]. Further investigations confirmed an important role of internal boundaries in acoustic nonlinearity enhancement for dislocations in fatigued materials and matrix-precipitate interfaces in alloys [2].

Further experiments revealed a substantial increase of nonlinearity in non-bonded contacts of cracked defects due to specific contact acoustic nonlinearity (CAN) [3]. Besides the higher efficiency, CAN was shown to accommodate the effects of frequency down-conversion (subharmonics), hysteresis, instabilities, chaotic dynamics,

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etc. [4]. To interpret such unconventional behavior the damaged area was assumed to manifest both nonlinear and resonance properties [5]. A direct experimental proof for the "resonant" defects has been obtained recently [6] and the concept of Local Defect Resonance (LDR) introduced.

In this paper, the effect of LDR on nonlinear ultrasonic response of defects is studied. Unlike the resonance of the whole specimen, the LDR provides an efficient energy delivery from the wave directly to the defect, so that it manifests a profound nonlinearity even at moderate ultrasonic excitation level. A combined effect of LDR and nonlinearity also results in new "nonclassical" features (subharmonics, hysteresis, instability) characteristic of nonlinear and parametric resonances. It is shown that the ultrasonic activation of defects by using the concept of LDR is the way to optimize the sensitivity and efficiency of nonlinear ultrasonic imaging and NDT.

2. LDR nonlinearity and nonlinear resonances

Since LDR is as an efficient resonant "amplifier" of the local vibrations, one would expect it to contribute appreciably to defect nonlinearity. To identify LDR frequency of a defect (ω_0), ultrasonic excitation by a wide-band piezoelectric transducer was combined with a laser vibrometer (PSV 300 Polytec) scan of the specimen surface. An extremely high resonant nonlinearity is demonstrated in Fig. 1 for a delamination in a glass fiber-reinforced (GFRP) composite plate: Multiple HH generation is observed even at a moderate input voltage. A crucial role of the driving frequency match to LDR for increase of nonlinearity is illustrated in Fig. 2 for a crack in a unidirectional (UD-) carbon fiber-reinforced (CFRP) rod. As the driving frequency matches the LDR frequency (19.5 kHz), a strong enhancement of the HH amplitudes generated locally in the defect area is observed.

A high quality factor of LDR can also be used as an "amplifier" in the frequency mixing nonlinear NDT. 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: $f_\pm = f_1 \pm f_2$. An application of LDR as the "frequency mixing amplifier" for NDT and imaging of realistic defects is illustrated then in Fig. 3, 4. for an impact induced damage (area ~5x5 mm^2) in CFRP plate (280x40x1 mm^3) with LDR frequency around 110 kHz (Fig. 3). In the experiment, the two interacting flexural waves were excited in a continuous wave mode by using 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. Fig. 4 shows the 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. 3: more than 20 dB increase in the output is observed when the combination frequency matches the frequency of LDR. This approach is applicable to any geometry of the wave interaction since LDR response is weakly sensitive to its position in the wave field.

The results presented in Figs. 1-4 prove that 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 frequency 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 results in efficient frequency conversion into HH and subharmonics via superharmonic and subharmonic resonances.

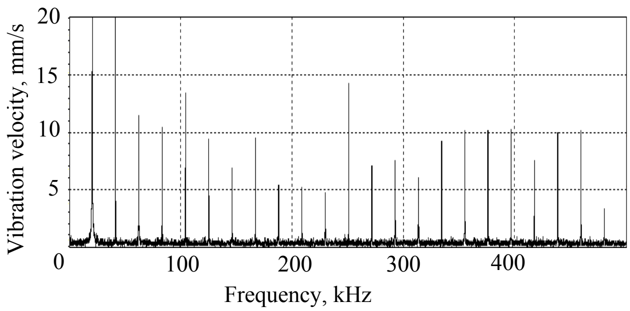

Fig. 1. HH spectrum for delamination in GFRP specimen driven at LDR frequency 20900 Hz. Input voltage is 7 V.

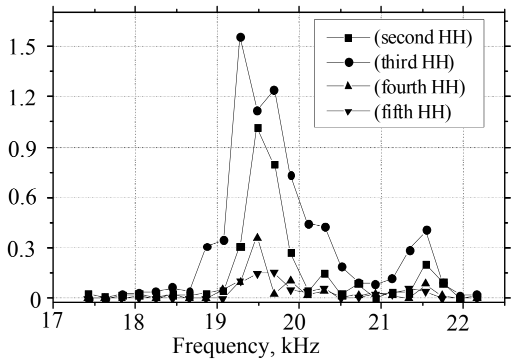

Fig. 2. HH LDR frequency response of a crack in CFRP rod (LDR frequency 19.5 kHz).

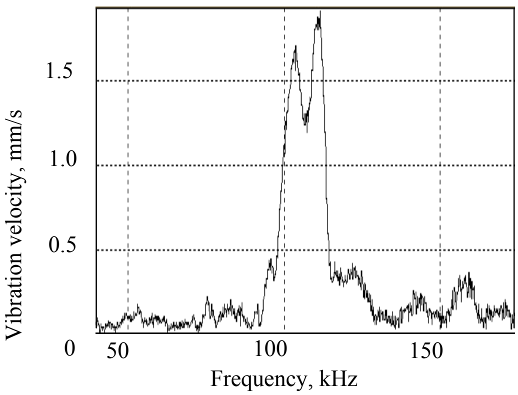

Fig. 3. LDR frequency response for an impact induced damage in a CFRP plate.

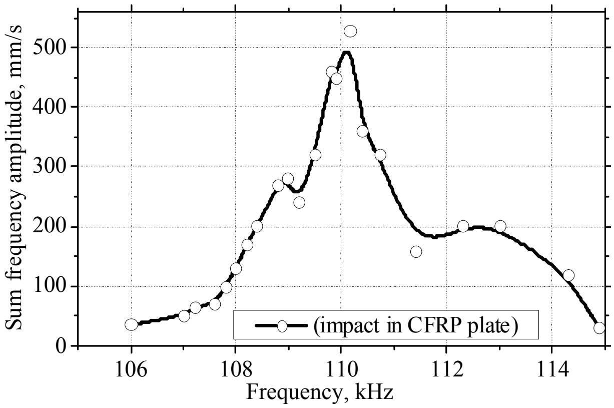

Fig. 4. LDR induced amplification at the sum frequency vibration for impact damage in a CFRP plate.

2.1. Superharmonic LDR

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 defect. A direct proof of superharmonic resonances in defects is demonstrated for the third-order resonance in impact damaged CFRP specimen with LDR around 5140 Hz in Fig. 5. One-third of the LDR frequency (1714 Hz) was selected for the excitation and the input voltage was increased up to 80 V. The spectrum (Fig. 5) of the defect vibrations measured in the defect area beyond the threshold illustrates the dominance of the third harmonic: the third harmonic amplitude is ~25 dB higher than fundamental frequency component. In a similar experiment for 2570 Hz input ($n = 2$), the second-order superharmonic resonance revealed somewhat lower efficiency of frequency conversion (~10 dB) due to generally lower second-order nonlinearity of CAN.

2.2. Subharmonic LDR

To observe the resonant growth of subharmonic the excitation frequency was changed to the second harmonic (10280 Hz) of the fundamental LDR for the impact damage in CFRP. 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 10280 Hz input (Fig. 6). The input frequency range for both subharmonic and superharmonic resonances was measured to be within ~100-200 Hz that corresponds to a high Q factor of the LDR for this defect. Both super- and subharmonic resonances were observed reliably for a variety of defects in composite materials and therefore complement "classical" nonlinear NDT modes, like HH and frequency mixing.

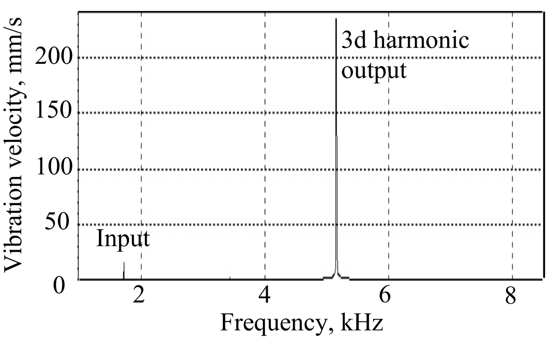

Fig. 5. Spectrum of the third-order superharmonic LDR in impact damaged CFRP plate.

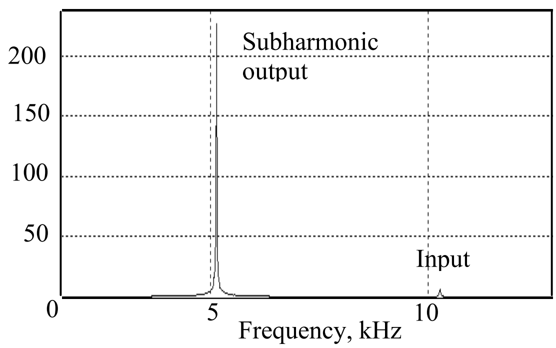

Fig. 6. Subharmonic spectrum for LDR of impact damage in CFRP beyond threshold input voltage 45 V.

3. LDR nonlinear imaging

Under LDR condition, new nonlinear frequency components are generated efficiently and highly localized in the defect area that provides a background for the high-contrast defect-selective imaging. The benefit of the higher harmonic LDR imaging is illustrated in Fig. 7. A substantial improvement of the image quality (10x20 mm^2 delamination in a GFRP plate) is clearly seen by comparing the fundamental (signal-to-noise ratio ~12dB) and the second harmonic (signal-to-noise-ratio ~24dB) images.

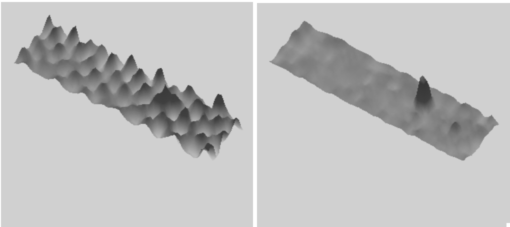

Fig. 7. Linear (36.77 kHz, left) and second harmonic (73.53 kHz, right) LDR imaging of a delamination in GFRP specimen.

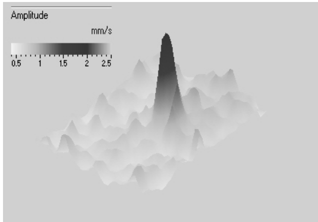

Fig. 8. Sum-frequency image of the impact-induced damage (~5x5mm^2) in a CFRP plate.

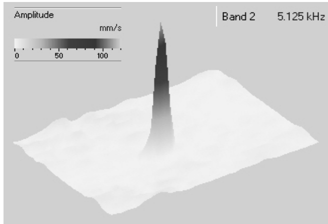

Fig. 9. Subharmonic LDR imaging of impact damage in a CFRP plate: Input 10250 Hz; output 5125 Hz.

Other examples of the resonance nonlinear imaging are given in Figs. 8, 9. The LDR contribution to the sum-frequency signal makes it localized in the damage area and enables to be used for mixing frequency imaging with reasonable signal-to-noise level (~15 dB, Fig. 8). This image of the impact in a CFRP plate was obtained by mixing flexural waves of frequencies 77 kHz and 30 kHz via combination frequency resonance (LDR frequency of the defect 107 kHz). The benefit of subharmonic LDR is illustrated in Fig. 9 for the impact damage in CFRP specimen.

Conclusion

A combination of nonlinearity with LDR enhances substantially the efficiency of "conventional" nonlinear effects, like HH generation and frequency mixing, and results in qualitatively new "nonclassical" features characteristic of nonlinear and parametric resonances. According to the experiments, under LDR conditions the HH, frequency mixing and subharmonic components may dominate in vibration spectrum of defects. This suggests nonlinear LDR application as an extremely 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-selective imaging. The resonant nonlinear modes require much lower acoustic power to activate the defects that makes it possible to avoid high-power instrumentation.

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