NONLINEAR ULTRASONIC INSPECTION AND NDE USING SUBHARMONIC AND SELF-MODULATION MODES

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Abstract

It has been shown recently that a dramatic increase in local acoustic nonlinearity is obtained for imperfect and damaged areas in solids due to inherently nonlinear vibrations of non-bonded contacts inside fractured defects. The mechanisms of the contact nonlinearity are quite different from the „classical" nonlinearity and bring along a family of „non-classical" nonlinear phenomena (subharmonics, instabilities, chaos, etc.).

In the present paper, new opportunities of applications in nonlinear acoustic NDE and imaging are shown for multiple subharmonic, self-modulation and chaotic modes observed in our experiments. The experimental methodology includes a high power single-point acoustic excitation combined with remote scanning laser vibrometry. High contrast images are obtained for various realistic defects (delaminations, cracks, impacts, etc.) in a number of materials (plastics, composites, wood, etc.) using the new nonlinear modes.

Introduction

Most of the current ultrasonic inspection systems are "linear" systems, i.e. they detect some linear elastic parameters of flaws responsible for sound transmission and reflection inside the sample. Detecting and imaging of local elastic nonlinear properties has always been a challenging task with possible promising outcome for seismology, medical diagnostics, material characterisation and NDE applications. A feasibility of such nonlinear acoustic NDE-modes depends on nonlinearity of defect areas which determines the efficiency of local nonlinear signal generation and eventually the contrast of the nonlinear image.

The opportunities of defect imaging using a very high local nonlinearity of cracked defects have been shown using the higher harmonic generation [1] and wave mixing (nonlinear modulation [2]). However, an account for nonlinear resonance properties of cracks [3] results in a new group of nonlinear phenomena: fractional subharmonics, instability, hysteresis, self-modulation and dynamic chaos are observed in acoustic wave interaction with defects [4]. Since these effects are based on a local manifestation of the contact nonlinearity they, apparently, can be applied to locating and imaging of the nonlinear defects.

The paper reports on the study of the resonance effects of contact nonlinearity and their adaptability in the new modes of nonlinear acoustic NDE. First, we briefly discuss a background of the phenomena concerned with nonlinear and parametric resonances. New experimental features are demonstrated in the next section followed by the results of nonlinear imaging of flaws in application oriented materials.

Phenomenological background

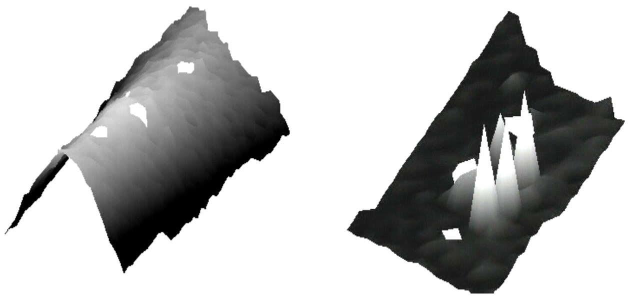
A certain area (and mass) of material coupled to a cracked defect exhibits a reduced average stiffness and thus its resonance properties are supposed to be different from the outside intact area. For an intense drive signal, such a damaged area can be considered as a highly nonlinear oscillator whose nonlinearity is determined by modulation of the contact stiffness due to clapping and nonlinear friction mechanisms [3]. For the same reasons, the defect area is also a parametric oscillator: temporal change in the contact stiffness leads to parametric modulation of its eigen-frequency ω described by a Hill differential equation:

$$\ddot{x} + \omega(t)x = 0 \quad , \qquad (1)$$

where $\omega(t)$ is a periodic function of the modulation frequency ν_m.

Solutions to (1) are well-known [5] and exhibit resonant amplification (instability) of the output frequency components $\omega_{out} = (K+2n)\nu_m/2$ observed for integer values of $K = 2\omega/\nu_m$. Therefore, the output frequency of the parametric oscillator varies from the sum of subharmonics (K is odd) to multiple higher harmonics (K is even). The main parametric resonance corresponds to $K=1$ and results in a series of subharmonics of order 1/2. Dynamic characteristics of parametric oscillations feature a must threshold of the input and an output amplitude "jump" (instability) beyond the threshold.

If one assumes a multi-mode structure of the defect area oscillations (e.g. eigen-frequencies $n\omega_1$ and $m\omega_2$) the parametric phenomena can follow a different scenario [6]: the main parametric resonance can result in simultaneous parametric excitation of a pair of resonance modes $\Omega_1 = n\omega_1$ and $\Omega_2 = m\omega_2$ as soon as the subharmonic of the modulation frequency lies in the middle between them:



a) b)

Figures 1a, b: Vibration patterns of cracked FR-ceramic sample: a) bending mode sample resonance (1350 Hz); b) one of the resonance modes of cracked area (≈ 81 kHz). The holes (seen in the picture) are made to initiate cracking.

$\Omega_1 = (\nu_m/2) - \Delta$; $\Omega_2 = (\nu_m/2) + \Delta$.. Successive nonlinear interaction between ν_m, Ω_1, and Ω_2-components results in a line spectrum with side-lobes around the subharmonics $(2n+1)(\nu_m/2) \pm \Delta$ and near the higher harmonics $n\nu_m \pm 2\Delta$. The presence of the side-lobes is an indication of amplitude modulation (parametric "self-modulation") of the output.

As the driving amplitude increases, the instabilities develop successively for the higher-order fractional subharmonics and the "self-modulation" frequency pairs. Eventually, it will bring the system into chaotic temporal behaviour with a noise-like vibration pattern and a quasi-continuous spectrum [4].

Experimental features of nonlinear resonance instability

The experiments were carried out in the frequency range up to 100 kHz with a series of polymer and composite samples containing cracked defects (cracks, delaminations, impacts, etc.). An electrodynamic shaker (input current 1-5 A) was used to excite low-frequency (1-5 kHz) vibrations. To produce higher frequency intense vibrations, an ultrasound piezoelectric stack transducer was driven with a CW electric signal. A scanning laser vibrometer was used to detect and image out-of-plane surface vibrations. After FFT of the output signal, the area scans of the sample surface were obtained at any spectral line over the frequency band of 1 MHz.

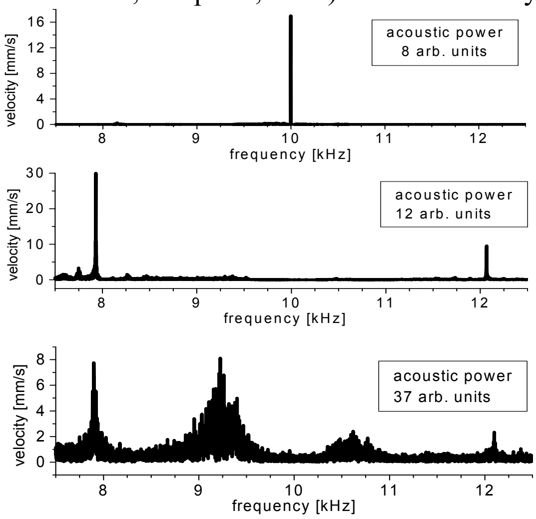
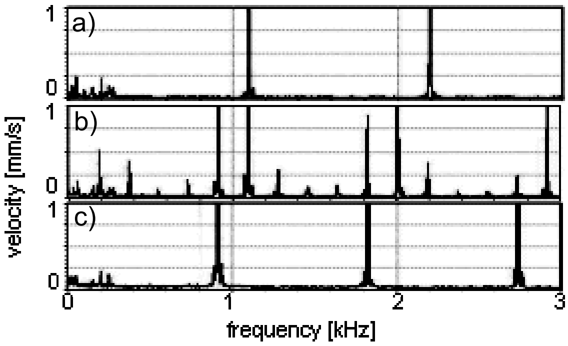


Figure 2: Subharmonic-frequency pairs-frequency bands series in a delamination area in C/SiC ceramic sample.



Figures 3a, b, c: Interchangeable generation of subharmonics (a, c) and frequency pairs (b) by a crack in a polystyrene plate.

Figures 1a, b show the amplitude scans of fibre-reinforced (FR-) ceramic sample obtained at two different frequencies. One can easily see that a linear resonance of the whole sample (bending mode) is excited at 1350 Hz while a strong excitation of the cracked area inside the sample occurs at different resonance frequencies. Due to clapping, the latter behaves like a typical nonlinear oscillator and demonstrates subharmonic parametric resonance performance.

Dynamic properties of the clapping nonlinear oscillator (delamination area in C/SiC ceramic plate) shown in Figures 2a-c reveal the threshold behaviour of the subharmonic instability (a) followed by the frequency pair bifurcation ($2\Delta \approx$ 4.2 kHz) at higher inputs (b). Further increase in the input initiates enhancement of the background noise in the form of noise-like frequency bands which appear symmetrically around the subharmonic frequency (c). This shows that a series of subharmonic - frequency pairs (self-modulation) - noise-like frequency bands - is a parametric scenario for transition to dynamic chaos in cracked defects.

A typical frequency response of a sample with nonlinear cracked defect above the subharmonic threshold is illustrated in Figures 3a. b, c. In full accord with the parametric approach, the variation in the driving frequency ν_m results in excitation of subharmonics for two resonance modes ($\Omega_1 \approx 900$ Hz and $\Omega_2 \approx 1100$ Hz) if $\nu_m = 2\Omega_1$, $2\Omega_2$ (Figures 3a, c). When $\nu_m \cong \Omega_1 + \Omega_2 \cong 2000$ Hz both resonance modes are excited and frequency pairs dominate in the output spectrum (Figure 3b). For realistic cracked

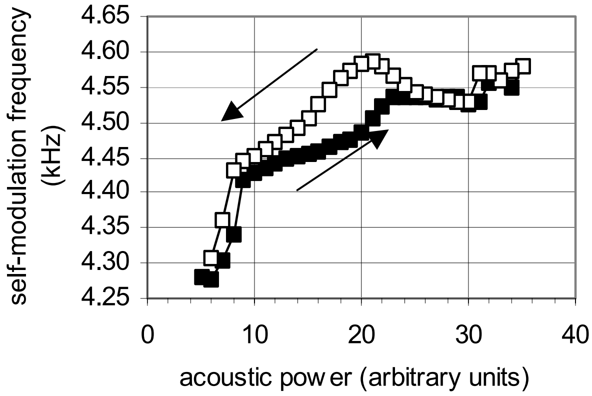


Figure 4: Self-modulation frequency (2Δ) as a function of input acoustic power. Arrows indicate the directions of power variation.

defects, the interchangeable excitation of the subharmonics and frequency pairs normally continues in a wider frequency range that reveals the presence of a multi-modal structure of resonances.

The fine structure of their dynamic nonlinear behaviour is given in Figure 4 which demonstrates that the distance between the side-lobes in a frequency pair 2Δ (self-modulation frequency) depends on the amplitude of acoustic excitation. This fact (also noted in [7]) is in line with performance of nonlinear oscillators whose resonance frequencies are to be amplitude dependent. The bistability of 2Δ clearly seen in Figure 4 is also a characteristic feature of nonlinear resonance phenomena [8].

Thus, the experiments reveal that the model of a multi-modal nonlinear and parametric oscillator describes adequately basic features of nonlinear dynamics of a cracked defect.

New modes of nonlinear NDE

Subharmonic mode

Since the subharmonic generation is caused by a local nonlinear resonance in a defect area, it can be used for locating and imaging of that area provided the acoustic wave input is beyond the threshold level. The latter was found to be reasonable (within 20-40 W of acoustic power), mainly, for loose cracks and delaminations. A few examples of the subharmonic defect imaging are presented in Figures 5-7 for

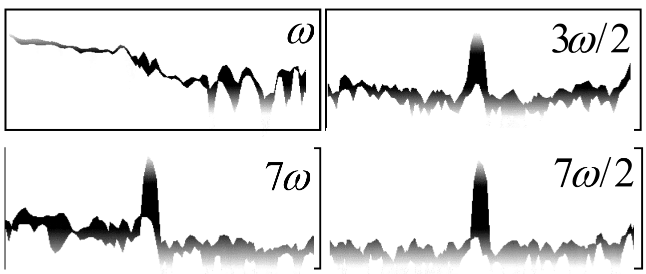


Figure 5: Linear , higher harmonic and subharmonic images (B-scans) of a knot in the middle of a 50 cm-long wooden rod. Vibrations are excited at the left-hand side edge of the specimen.

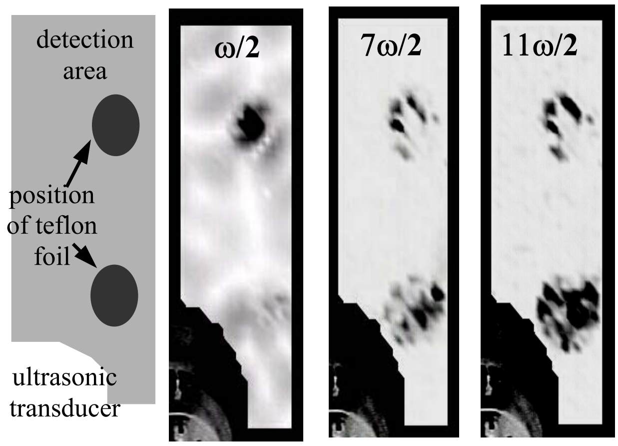


Figure 6: Subharmonic images of simulated delamination area in a Glare® sample

various constructional materials.

Figure 5 is a comparison between the linear, higher harmonic and subharmonic imaging of a cracked knot area in a wooden rod. All subharmonic images clearly reproduce the defect area, whereas a decent image for the higher harmonic mode is obtained only by the 7th order higher harmonic.

Another example (Figure 6) is concerned with a promising material for aircraft industry: glass fibre reinforced aluminium laminate (Glare®). Metal-fibre-laminates are new high-tech materials with excellent tolerance to impact, corrosion, lightning stroke, low flammability and a low weight. However, due to reduced plastic deformation delaminations can occur during the production process that requires NDE-techniques in service and maintenance.

Figure 6 shows the subharmonic images of the Glare® plate with two inserted circular Teflon-foils to simulate local debonding. One can notice the image quality enhancement for the higher numbers of subharmonics (of the ½-order). The latter may, apparently, be associated with the higher acoustic dissipation outside the delamination area.

In accord with the parametric approach, to optimize the subharmonic excitation one should make a proper choice of the driving frequency to excite the parametric resonance of the defect area. An example

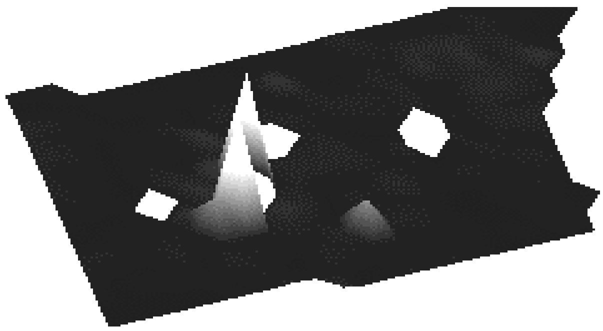


Figure 7: Subharmonic image of cracked area in FR-ceramic. Excitation frequency ≈ 27 kHz corresponds to one of the resonance frequencies of the defect.

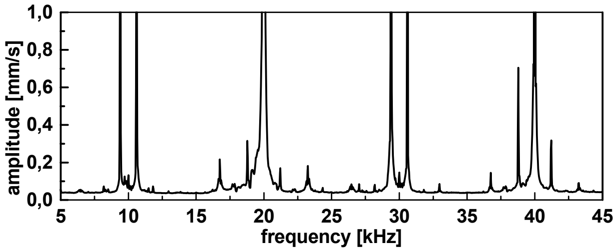


Figure 8: Self-modulation spectrum for the sample of a epoxy-based textile composite with an impact. Excitation frequency is 20 kHz.

of such an optimization is shown in Figure 7. Excitation of the cracked area in the FR- ceramic sample at one of the linear resonance frequencies of the defect allowed to obtain the subharmonic imaging of the defect at a very low acoustic input.

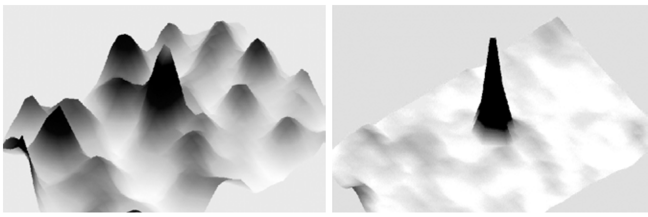
Self-modulation mode

From a user`s view point the frequency pairs can be used for nonlinear NDE similar to the combination frequency components in the nonlinear modulation technique [2]. However, since they arise on their own, the technique proposed is called “self-modulation” and can operate without an additional pump wave.

Figure 8 demonstrates the frequency pairs in the spectrum of nonlinear vibrations for the sample of multi-ply epoxy-based glass fibre-reinforced textile composite with an impact. Similar to the experiment in Figure 2, the frequency pair bifurcation replaces the subharmonic instability as input acoustic excitation increases. According to Figure 8, the self-modulation frequency in this experiment was $\cong 1.2$ kHz.

The benefit of the technique in locating cracked defects (impacts) is illustrated in Figures 9a, b for the same sample. The 4th harmonic image of the impacted area (in the centre part of the sample) is corrupted by the standing wave pattern (a). However, a very clear indication of the impact is demonstrated in Figure 10b where the image was taken at 198.8 kHz, i.e. at the side-lobe of the 10th harmonic of driving frequency.

The signal-to-noise ratio for the maximum in Figure 9b exceeds 20 dB. Vibrometric measurements of the absolute values of vibration velocity enable to estimate the efficiency of the self-modulation: for the peak value of the 10th harmonic amplitude $\cong 750$ μm/s, its anti-Stokes side-lobe was as high as $\cong 600$ μm/s in the impact area. It shows that the efficiency of the frequency pair generation is comparable to that of the higher harmonics.



a) b)

Figures 9a, b: Self-modulation imaging of an impact in GFR-composite: a) 4th harmonic image; b) self-modulation (side-lobe of the 10th harmonic) image.

Summary

An area around defects with non-bonded contacts exhibits a reduced average stiffness and resonance properties that differ from the outside intact area. For an intense acoustic drive, such a damaged part of material behaves like a highly nonlinear and parametric oscillator. As a result, the resonance effects of dynamic instability develop in the form of subharmonic, frequency pair and chaotic oscillations. These effects are localized in the damaged area that makes them applicable to locating and imaging of defects. Though more complicated physics is involved, the new nonlinear NDE methodologies based on the instability phenomena are found to possess positive benefits as compared to the higher harmonic and wave modulation techniques.

Acknowledgement

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