New modes of Nonlinear Ultrasonic Resonance Spectroscopy (NURS) for early defect recognition and imaging

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Introduction

Classical ultrasonic spectroscopy uses material linear frequency response to the input signal which depends on variations in the eigen-frequencies of the component in the presence of defects. Such a linear spectroscopy is widely used in industry and technology for material characterisation and quality assessment, despite the fact that boundary conditions like geometry variations can falsify the result.

The nonlinear approach to NDE discussed in this paper is concerned with non-linear material response, which is related to intrinsic frequency changes of the input signal due to acoustic wave interaction with material flaws and assumes resonances of the defect area.

As a result, in addition to the eigen-frequencies the NURS acquires new nonlinear frequency components (higher harmonics, subharmonics, frequency side-lobes, etc.) that carry information on local material imperfection. By monitoring the local nonlinear spectral response, the nonlinear NDE modes appeal directly to the vulnerable (faulty) areas within a material or a product.

Background of Nonlinear Resonance Spectroscopy

It was shown that the cracked defect (as well as the damaged sample) could be considered as a strongly nonlinear inclusion in the intact material [1]. We also assume that the sample (or the defect area) exhibits some resonance properties, that turns it into a nonlinear oscillator. In this case, the nonlinear response acquires the following main features:

- resonance frequency shift which depends on the amplitude
- jumps (instability) of the output amplitude as a function of frequency and amplitude of excitation
- frequency and amplitude hysteresis (bistability).

Under these conditions acoustic wave interaction with a defect results in several new spectral properties like threshold higher harmonics, subharmonics, and frequency pairs, which will be shown to be applicable to NDE.

Resonance Frequency Shift

Nonlinear vibrations of a cracked defect driven by an acoustic wave result in a local stiffness modulation due to “clapping” between the crack surfaces. As the driving amplitude increases, so does the crack opening phase that makes the nonlinear oscillator “soft”. Therefore, the peak of its resonance frequency response is expected to shift to the lower frequency (Fig. 1). Specific distortion of the curves in Fig. 1 clearly indicates the instability of the output amplitude which corresponds to a singularity of their first derivative and demonstrates the hysteretic behaviour of nonlinear oscillations [2].

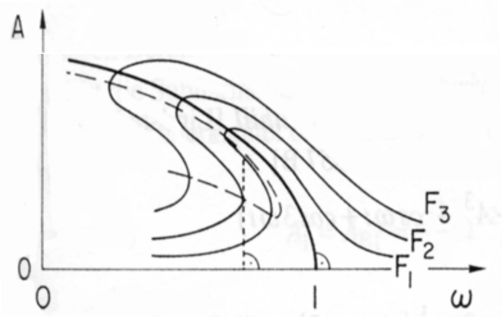

Figure 1: A typical frequency responses of a “soft” nonlinear oscillator (a crack) for various driving forces (F).

Subharmonic Mode

Consider a nonlinear interaction of the acoustic wave (frequency ν) with the cracked defect (eigen frequency ω). In the quadratic approximation, the acoustic wave impact produces the driving forces of the combination frequencies ($\nu \pm \omega$). The difference frequency component will result in the nonlinear resonance if $\nu - \omega \approx \omega$ or $\nu = 2\omega$. Thus, the nonlinear growth of the crack oscillations (frequency ω) takes place for the driving frequency 2ω (subharmonic resonance). Such phenomena fall into a class of parametric resonance phenomena that feature a “jump” of the subharmonic amplitudes (instability) beyond a certain threshold. Their avalanche-like growth turns the output spectrum into a series of the subharmonics integer multiples of the $\nu/2$.

Frequency Pairs

Assume now that the defect is more complicated and comprises a set of coupled nonlinear oscillators (eigen frequencies ω_i). For any pair out of these frequencies (ω_1 and ω_2) in the quadratic approximation the driving forces of the combination frequencies are produced: $\nu - \omega_1$ and $\nu - \omega_2$. Similar to the above, the resonance growth of ω_1 - and ω_2 -vibrations will be observed if both frequencies satisfy the relation: $\omega_1 + \omega_2 \approx \nu$ (frequency pair generation). The higher-order nonlinear interaction leads to a line spectrum with side-lobes around the subharmonics and higher harmonics. The presence of the side-lobes is an indication of amplitude modulation (parametric "self-modulation") [3].

Experimental Results

Equipment

To excite intense acoustic vibrations in the specimens (predominantly flexural waves) we used a set of ultrasound piezoelectric stack transducers driven with a CW electric signal of maximum electric power 2kW in the frequency range 15-40 kHz. Due to insertion and coupling losses the acoustic power transmitted into a sample was usually within 10-30 W to provide a non-destructive but substantially nonlinear regime of measurements. A scanning laser vibrometer was used for detection and imaging of out-of-plane nonlinear vibrations. After scanning the specimen at every point, the time signal of the harmonic vibration was transformed into frequency range so that the C-scan images are obtained for any spectral line within the frequency bandwidth of 1 MHz.

Resonance Frequency Shift

To verify a feasibility of the NURS approach we, first, studied the nonlinear resonance frequency shift for the sample of a carbon fibre reinforced plastic (CFRP) with a damaged area (impact). As the input voltage increases from 5 to 50 V the peak of the sample frequency response demonstrates the shift of about 5% to the lower frequency range. This is in accord with the model developed above and can be explained by a lower average stiffness of the cracked defect at higher amplitudes.

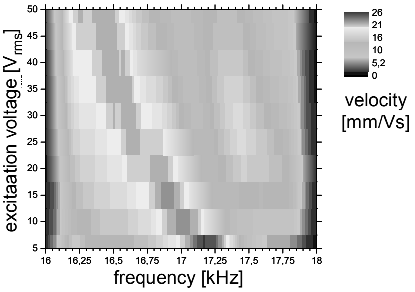

Figure 2: Resonance frequency shift for CFRP sample with impact damage (up-sweep 16-18kHz).

Subharmonic NURS

Normally the resonance frequency shift is an indication of the input amplitude to be high enough to observe the resonance instability modes. In this range of the input amplitude, the subharmonic mode demonstrates the threshold behaviour: a step-like "jump" and saturation for further increase of the input. The examples of the C-scan imaging with the subharmonic NURS-modes are shown in Figs. 3 and 4. For the excitation frequency 20 kHz, the $\omega/2$-subharmonic demonstrates about 20dB increase in the damaged area in the CFRP laminate (Fig. 3).

Fibre reinforced Al_2O_3 ceramics is a new material used for thermal insulation which is "inconvenient" for acoustic NDE due to its high porosity and woven structure. Fig. 4 shows that the subhamonic NURS clearly detects delaminations in this material.

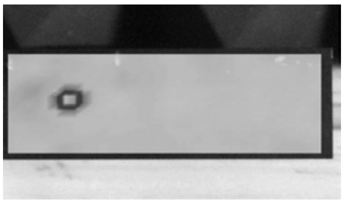

Figure 3: $\omega/2$-image of damage in CFRP sample (14,5x4cm).

Figure 4: $3\omega/2-$ NURS of delamination areas in fibre reinforced aluminium oxide ceramic (9,5x 5,5cm).

Frequency Pair NURS

Frequency pair generation is normally observed beyond the subharmonic threshold and brings about a number of new frequency lines around both subharmonics and higher harmonics. According to Fig. 5, the frequency pair components are also localized in the nonlinear source area and provide nonlinear acoustic imaging of the defect.

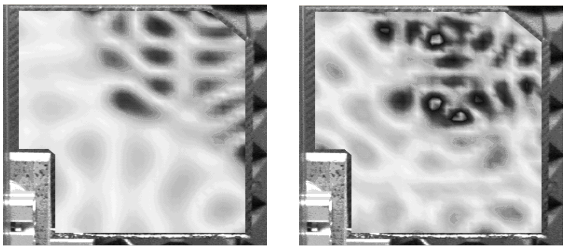

Figure 5: NURS of C/C-SiC-fibre reinforced composite with large delamination: excitation frequency 20 kHz; frequency pair images 32,25kHz (left) and 47,75kHz (right).

Conclusion

The NURS approach developed is based on the nonlinear resonance phenomenon that is characteristic of the damaged materials. The resonance nonlinear interaction of the acoustic wave with cracked defects results in nonlinear shift of resonance frequency, fractional subharmonic and self-modulation instabilities. The new NURS modes manifest strong localisation in the defect area and are suitable for nonlinear defect selective imaging and NDE.

References

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[2] F.K.Kneubühl: Lineare und nichtlineare Schwingungen und Wellen. Teubner, Stuttgart, 1995.

[3] I. Solodov, B. Korshak, K. Pfleiderer, J. Wackerl and G. Busse: Nonlinear ultrasonic inspection and NDE using subharmonic and self-modulation modes, Proc. World Congress on Ultrasonics, pp. 1335-1338, Paris, 2003.