A local defect resonance to enhance acoustic wave-defect interaction in ultrasonic nondestructive evaluation

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It is experimentally shown that, to provide maximum acoustic wave-defect interaction, the concept of a local defect resonance should be applied. The model of a resonant defect is used for the selection of the wave frequency to enhance the excitation of the defect in nonlinear acoustics and ultrasonic thermography. An increase in nonlinear response of the defect at its local resonance exceeds substantially the one at natural frequencies of the specimen. The strong wave-defect interaction is confirmed by resonance induced rise of local temperature of the defect in the frequency band of its local resonance. © *2011 American Institute of Physics*. [doi:10.1063/1.3663872]

Ultrasonic wave interaction with mechanical inhomogeneities in solids is widely used for nondestructive evaluation (NDE) of materials and industrial components. Traditional ultrasonic instruments make use of a linear wave-defect interaction, which results in amplitude and phase variations of the input signal. Recent developments, such as nonlinear methodology and ultrasonic thermography, concern with nonlinear and thermal responses of defects, which require higher wave energy to activate the defect. In both cases, NDE-methodology is based on choosing the wave frequency equal to one of the natural frequencies of the specimen[1–3] or on producing a quasi-chaotic acoustic excitation to increase the vibration amplitude over a wide frequency spectrum.[4]

Alternative approaches, used in nonlinear acoustics of air bubbles in water[5] and contrast agents,[6] introduce a resonance frequency of the soft inclusion as a key factor to increase the ultrasonic response of the insonified inclusion. Likewise, the opportunity of a resonance interaction of Lamb waves with defects in solids was theoretically analysed.[7] A similar phenomenology of “resonant” defects was used to describe the nonlinear dynamics of flaws in solid materials.[8] Recent numerical simulations and shearographic imaging demonstrated a modal vibration structure for delaminations in solids.[9]

In this letter, the concept of the resonant defect is further developed and applied to select the wave frequency in order to optimize the local excitation of the defect. By using laser vibrometry, the resonance frequency response is measured and visualized for a delamination in composite material. The higher harmonic response of the defect measured at its resonance frequency exceeds dramatically the one obtained at the natural frequencies of the specimen. The strong wave-defect interaction also causes a strong rise of local temperature in the frequency band of the defect mechanical resonance.

The local defect resonance was studied for an oval horizontal delamination (25×18 mm) formed due to debonding of adjacent plies at ≈1 mm depth in a 12-ply glass fibre-reinforced composite plate ($200 \times 25 \times 2.6$ mm). A piezoelectric transducer embedded in the plate was used for a wide-band (400 Hz–40 kHz) excitation of flexural waves. For this purpose, a pseudo-random input electrical voltage (amplitude 1–70 V; flat frequency response within 0-50 kHz) was applied to the transducer. The out-of-plane particle velocity components and the wave vibration pattern in the specimen were measured and visualized by a scanning laser vibrometer.

The amplitude spectrum of out-of-plane vibrations space-averaged over the top surface of the entire specimen (without time averaging) is shown in Fig. 1. The origin of each maximum in Fig. 1 was verified by filtering and imaging the wave pattern in the specimen at the corresponding frequency. The pattern in Fig. 2(a) illustrates one of the specimen length resonances, which are located in the frequency range below 10 kHz in Fig. 1. Similarly, a series of peaks in the frequency band 10–19 kHz were found to be associated with the specimen width resonances. The specimen vibration pattern filtered at ≅20 kHz–resonance (Fig. 2(b)) reveals a strong enhancement (more than 20 dB) of the vibration amplitude locally in the defect area and is identified as a fundamental defect resonance. The 2D-image zoomed-in around the defect location (Fig. 3(a)) shows that the resonance response is inhomogeneous over the defect area with a particularly high-amplitude in the upper (active) part of the delamination. Multiple higher-order resonances with characteristic nodal lines in the defect area were also found in the frequency range up to 40 kHz and visualized by filtering of the output signal (Fig. 3(b)).

The resonance behavior of the horizontal near-surface delamination can be attributed to the resonance vibrations of the material layer (thickness D) above the defect. For a well-developed (detached) delamination, it can, therefore, be identified with a flexural resonance of a plate of thickness D clamped around the boundary. By using a circular plate approximation (radius a), the estimate of the first resonance frequency f_0 of the delamination is given by[10]

$$f_0 \cong \frac{3.2D}{2a^2}\sqrt{\frac{E}{12\rho(1-\sigma^2)}}, \qquad (1)$$

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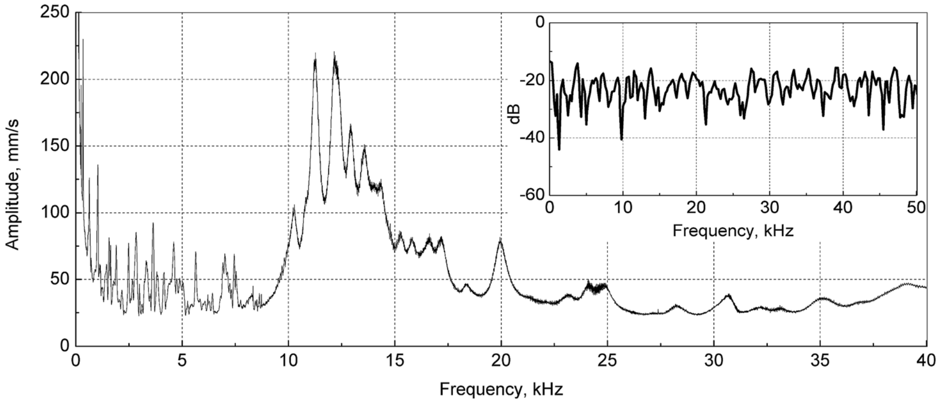

FIG. 1. Amplitude spectrum of out-of-plane vibrations averaged over the surface of the specimen studied. The inset shows a snapshot of the spectrum of the pseudo-random input signal.

where E is Young's modulus, σ is Poisson's ratio, and ρ is the density of the material.

For elastic constants of the material derived from the measurements of longitudinal and shear wave velocities ($E \approx 22$ GPa; $\sigma \approx 0.3$) and estimated values of density ($\rho \approx 2500$ kg/m^3), delamination depth, and size ($D \approx 1$mm; $a \approx 9$ mm), we obtain from Eq. (1) $f_0 \approx 19.8$ kHz, which is in perfect agreement with the experimental value of $\approx 20 \pm 0.2$ kHz.

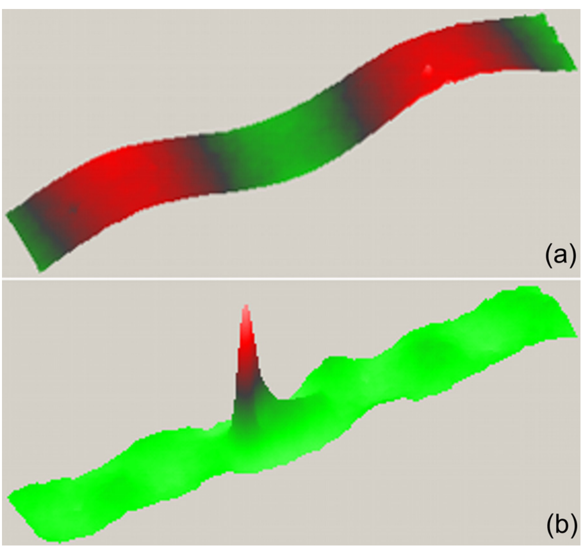

FIG. 2. (Color online) Vibration patterns at one of the specimen natural frequency (a) and at the fundamental defect resonance (b).

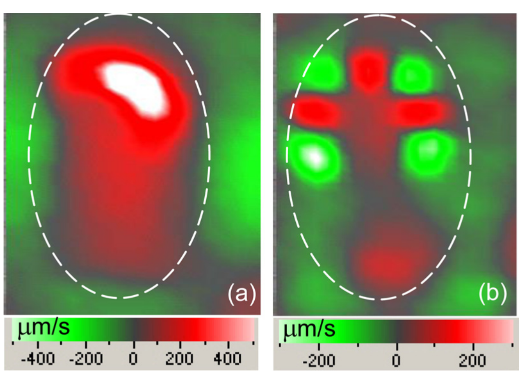

FIG. 3. (Color online) 2D-images of vibration modes for the fundamental resonance (filtered at 20 kHz, (a)) and for higher-order (filtered at 35.03 kHz, (b)) defect resonance.

The local resonance provides an efficient energy pumping from the wave to the defect that should result in a higher sensitivity of ultrasound to the presence of defects. This is of particular importance for power-dependent techniques such as nonlinear spectroscopy and ultrasonic thermography. By applying an ultrasonic wave with a frequency that matches the defect resonance, a substantial enhancement in efficiency of these methods can be expected.

This opportunity is demonstrated in Figs. 4 and 5 for the nonlinear ultrasonic response of the delamination measured for input signals of the specially selected frequencies. The amplitudes of the higher harmonics in the active delamination area increase by an order of magnitude within the bandwidth of the local resonance of the delamination (Fig. 4).

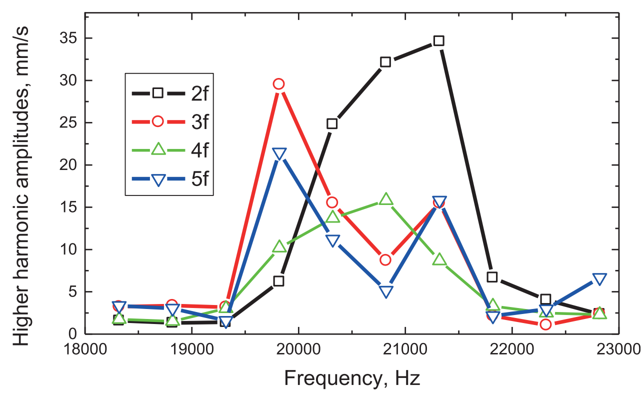

FIG. 4. (Color online) Higher harmonic amplitudes in the active part of delamination as functions of frequency in the band of the defect resonance response.

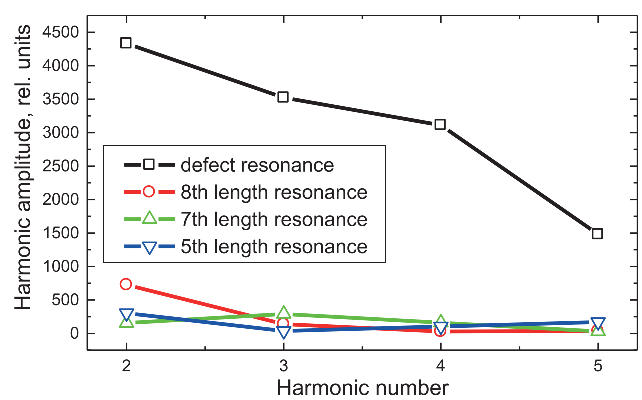

FIG. 5. (Color online) Comparison of the higher harmonic amplitudes measured in the active part of delamination at the local resonance frequency and at several natural frequencies of the specimen.

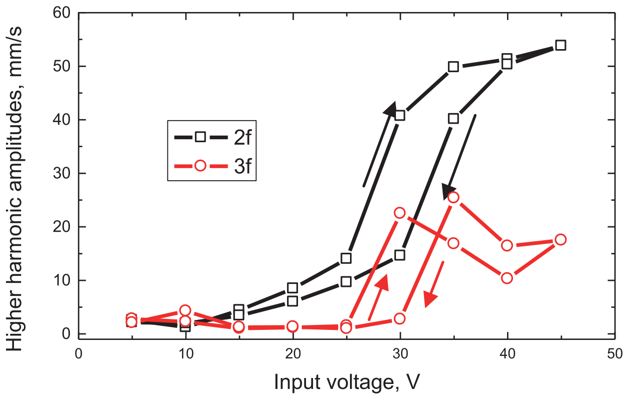

FIG. 6. (Color online) Bistability of the higher harmonics generated at the defect resonance frequency.

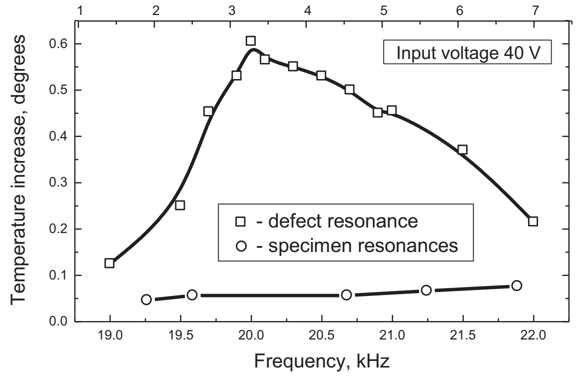

FIG. 8. Ultrasonic heating (maximum temperature rise over defect area) within delamination resonance response (lower frequency scale) and at the natural frequencies of the specimen (upper scale).

The measurements made at the natural frequencies of the entire specimen result in a much lower level of the higher harmonics in the same area (Fig. 5). The local resonance combined with a strong nonlinearity due to the clapping mechanism[11] specifies a defect as a nonlinear resonator and modifies fundamentally its nonlinear dynamics. In addition, Fig. 6 demonstrates that the higher harmonic generation acquires the characteristic features of instability modes: the step-like amplitude threshold and hysteresis (bistability).

The resonance increase in the out-of-plane vibration amplitude shown in Fig. 2(b) followed by clapping and rubbing of the delamination interface causes a local energy conversion into heat. The thermographic image of the defect taken at the resonance frequency 20 kHz (Fig. 7(a)) demonstrates that the heating is mainly produced in the active part of the delamination where the maximum vibration amplitude is observed (Fig. 2(b)). The maximum temperature rise in this area (for insonification time 15 s) as a function of frequency (Fig. 8) confirms the resonance character of the effect; the thermoacoustic imaging of the defect was only possible within the bandwidth of its resonance response 19-22 kHz. Outside this frequency range (including the specimen natural frequencies (Fig. 7(b)), the temperature increase in the same area was about an order of magnitude lower (Fig. 8) and barely measurable with the IR-camera (IRCAM Equus 327 K, sensitivity ≈20 mK).

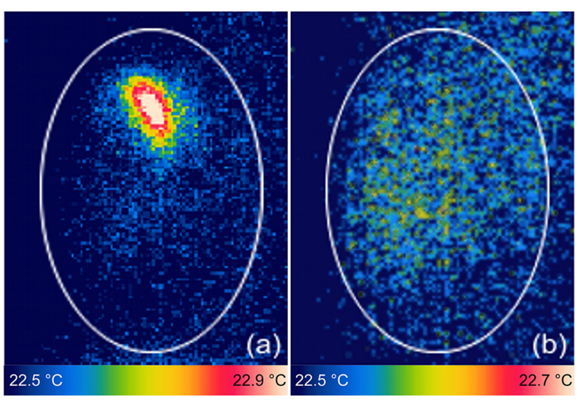

FIG. 7. (Color online) Thermographic images of the delamination at the fundamental defect resonance frequency (20 kHz, (a)) and at a frequency of one of the specimen length resonance (6.8 kHz, (b)).

In conclusion, it has been experimentally demonstrated that the concept of local mechanical resonance is applicable to the defects in solid materials. A single-frequency ultrasonic excitation is generally not an optimal way to inspect the material for defects. To optimize acoustic wave-defect interaction, a frequency match between the defect frequency response and the probing ultrasonic wave is required. In this condition, a substantial enhancement in efficiency is observed for ultrasonic methods applicable for linear, nonlinear, and thermographic non-destructive materials evaluation and testing.

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