ENHANCEMENT OF EFFICIENCY IN VIBRO- THERMOGRAPHY AND NONLINEAR ULTRASONIC NDT VIA LOCAL DEFECT RESONANCE (LDR)

Igor Solodov

University of Stuttgart, Institute of Polymer Technology, Department of Non-Destructive Testing (IKT-ZfP), 70569 Stuttgart, Germany
igor.solodov@ikt.uni-stuttgart

ABSTRACT

The concept of LDR is based on the fact that inclusion of a defect leads to a local drop of rigidity for a certain mass of the material and therefore manifests in a particular characteristic frequency of the defect. A frequency match between the driving ultrasonic wave and this characteristic frequency provides an efficient energy pumping from the wave directly into the defect. For simulated and realistic defects in various materials, the LDR-induced local increase in the vibration amplitude averages up to ~ (20-40 dB). Due to a strong resonance amplification of the local vibrations, the LDR-driven defects exhibit a profound nonlinearity even at moderate ultrasonic excitation level. The nonlinearity combined with resonance results not only in a strong generation of the higher harmonics but is also used as a filter/amplifier in the highly-efficient frequency mixing mode of nonlinear NDT. The LDR-thermography requires much lower acoustic power to activate defects that makes it possible to avoid high-power ultrasonic instrumentation.

Key words: Local defect resonance, ultrasonic thermography, nonlinear non-destructive testing.

1. Introduction

Ultrasonic nonlinearity and vibro-thermography (also called thermosonics or ultrasonic thermography) are promising approaches to NDT of materials and industrial components based, correspondingly, on nonlinear and thermal responses of defects exposed to ultrasonic excitation. They are both caused by relatively inefficient processes of clapping and/or frictional hysteretic rubbing at the defect interface and therefore depend critically on input ultrasonic power. As a result, both methodologies stand out from other conventional ultrasonic NDT counterparts for their specific instrumentation particularly adapted to high-power ultrasonics. The nonlinear techniques usually require a low-klirfactor generators and transducers combined with thorough filtering of higher harmonics barely possible for the high-voltage (hundreds volts) inputs. To provide a measurable temperature response, thermosonics traditionally employs high-power ultrasonic welding instrumentation, which includes kW-power supply (at fixed frequencies 20 or 40 kHz) and piezo-stack converters combined with ultrasonic boosters and horns [1]. The test specimen is usually pressed against the horn that results in unstable ultrasonic response and highly non-reproducible measurements.
In both cases, an increase in efficiency was found by using a resonant excitation of the specimen providing that the defect is outside the nodal areas of the standing wave pattern [2, 3]. This condition was shown to enhance the nonlinear defect response (higher harmonics, combination frequencies, etc.) and was applied in multiple experiments on nonlinear characterization of materials, e.g. [4]. In order to diminish the effect of nodal lines and to exclude “missing” the defect, the multi-mode analytical approach was developed [5]. It is based on selection of the specimen resonance modes with particularly high nonlinear responses for a given defect location. A possible drawback of a single-frequency ultrasonic excitation concerned with the nodal lines was also realized in ultrasonic thermography. To increase the probability of detecting a crack it was suggested to excite the specimens at multiple resonance frequencies instead of using a single-frequency excitation [6]. An enhancement in crack detectability by producing a wide-band excitation (“acoustic chaos”) was reported in [7]. The authors acknowledged that the origin of the effect might be related to elimination of vibrational nodes of the sample or correlated with the presence of the higher frequencies.

In this paper, a consistent way to enhance nonlinear acoustic and thermal defect responses is suggested by using selective ultrasonic activation of defects based on the concept of local defect resonance [8]. The LDR provides a selective excitation of a defect that results in a high local vibration amplitude and enhancement of both nonlinear and thermal defect responses readily measurable even for a few mW acoustic input.

2. Experimental evidence for LDR

A direct way to experimentally reveal LDR is to measure an individual contribution of each point of the specimen in its overall frequency response in a wide frequency range. For this purpose, an ultrasonic excitation by a wide-band piezoelectric transducer is combined with a laser vibrometer scan of the specimen surface. It enables to probe and indicate all possible resonances in every point of the specimen. The origin of each maximum is then verified by imaging the wave pattern in the specimen at the corresponding frequency. Fig. 1 shows an example of the LDR frequency response (a) and the vibration pattern (b) measured for a simulated defect (flat-bottomed hole (FBH)) in a PMMA plate. A strong enhancement (about 20 dB) of the vibration amplitude with a high Q-factor (Q ≈ 70) observed locally in the defect area is identified as a fundamental defect resonance (Fig. 1). Besides the fundamental LDR, zoom-in scan of the vibration field inside the defect area in a wider frequency range reveals the higher-order LDR with multiple nodal lines in the vibration patterns (Figs. 2, a-c). Such a methodology was successfully applied by us to a search of the LDR in a variety of materials [8]. The two examples presented in Figs. 3, a, b illustrate a clear evidence of LDR in kHz-frequency range for cracks and impacts in composite and constructional components. Similar LDR with local resonance “amplification” of the vibration amplitude as high as ~ (20-40 dB) were generally measured for other types of realistic defects.

3. LDR nonlinearity for defect imaging and NDT

Strong vibrations provided by LDR locally in the defect area should cause nonlinear effects even for simulated defects (FBH) driven by a relatively inefficient mechanism of material (“classical”) nonlinearity. Much higher nonlinearity is manifested by a variety of realistic cracked defects (delaminations, impacts, cracks, etc.) due to some different mechanisms.
Fig. 1: Frequency response (a) and vibration pattern at 11 kHz (b) for LDR in a circular FBH (10 mm radius and thickness 0.8 mm) in PMMA plate (200x40x4 mm$^3$).

Figs. 2, a, b, c: Higher-order LDR vibration patterns for a circular FBH in PMMA plate at different excitation frequencies: (a) mode (4,1) frequency 52.34 kHz, (c) mode (0,3) frequency 67.78 kHz, (c) mode (6,2) frequency 75.52 kHz.

Figs. 3, a, b: LDR vibration patterns for a 50 μm-wide and 10 cm-long crack in GFR-concrete specimen (frequency 4.19 kHz, (a)) and for an impact induced loss of fibres (area 25x2 mm$^2$) in a CFRP plate (frequency 3.66 kHz, (b)).

(contact acoustic nonlinearity (CAN), hysteretic nonlinearity, etc.). By combining the resonance conditions provided by the LDR with highly-efficient elastic nonlinearity (e.g. CAN) a substantial improvement in detecting and imaging of realistic defects by means of nonlinear NDT can be expected.

A strong increase in defect nonlinearity due to LDR is illustrated in Fig. 4 for a crack in a unidirectional (UD-) carbon fibre-reinforced (CFRP) rod. The zoom-in frequency response of the defect obtained for a wide-band excitation (Fig. 4, left) reveals the LDR-frequency $f_0 \approx 19500$
Hz. As the driving frequency matches the LDR-frequency, a drastic enhancement (~ 20-40 dB) of the higher-order harmonic (HH) amplitudes generated locally in the defect area is observed (Fig. 4, right).

Under the LDR condition, the higher harmonics 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. 5. A substantial improvement of the image quality (10x20 mm² delamination in 1 mm glass fibre-reinforced (GFRP) plate) is clearly seen by comparing the fundamental (left, signal-to-noise ratio ~12dB)) and the second harmonic (right, signal-to-noise-ratio ~24dB) images.

A high quality factor of LDR can also be used as a “linear” filter/amplifier in the frequency mixing nonlinear NDT. This method is based on the nonlinear interaction of ultrasonic waves of different frequencies (f₁, f₂) that results in a combination frequency output: fᵋ = f₁ ± f₂. For nonlinear experiments in “classical” materials (like, PMMA), the efficiency of interaction is highly critical to the geometry of the wave propagation and is generally rather low: the amplitude ratio Uᵋ/U₁₂ 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 the LDR response is weakly sensitive to the defect position in the wavefield.

In the experiment, the LDR induced “amplification” of the nonlinear interaction was studied for the FBH in PMMA plate (f₀ ≈11000 Hz) whose frequency response is shown in Fig. 1. The two
interacting flexural waves were excited in continuous wave mode by the piezo-transducers attached to the opposite edges of the plate. One of the frequencies was fixed at \( f_1 = 25 \text{ kHz} \), while \( f_2 \) was varied in the range of \((13500-14400 \text{ Hz})\) to provide the difference frequency \( f_- = f_1 - f_2 \) to sweep the LDR bandwidth of the FBH. The vibration velocity amplitudes (V) 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 difference frequency as a function of \( f_- \) measured by changing \( f_2 \) in the frequency range indicated above. The effect of LDR is clearly seen by comparing the data with those in Fig. 1. To quantify the amplification effect we estimate the interaction efficiency factor \( \eta = V_-/V_1V_2 \) [s/m] inside and outside the LDR bandwidth. The values obtained, correspondingly: \( \eta(11050) \approx 100 \) and \( \eta(10600) \approx 1.6 \) illustrate a strong increase in efficiency induced by LDR. The resonance amplification of nonlinear vibrations also provides unusually high amplitude of mixed frequency signal: at the optimal frequency match \( (f_- = f_0) \), the amplitude ratio \( V_-/V_2 \approx 44\% \) and \( V_-/V_1 \approx 93\% \).

Fig. 6: LDR induced amplification of the difference frequency vibration measured for an FBH in PMMA specimen.

4. LDR vibro-thermography

In ultrasonic thermography, the defect thermal response is caused by a local dissipation of mechanical energy, which is converted into heat. In the frame of viscoelastic model, this process is described by introducing the internal friction force proportional to velocity of vibration so that \( \sigma \sim E^\omega \dot{\epsilon} \) energy loss per unit time is:

\[
\Delta W = \frac{\omega^2 \varepsilon_0^2 E \dot{\epsilon}}{2} .
\]

According to (1), the dissipated power is proportional to the square of both the frequency (\( \omega \)) and the amplitude (\( \varepsilon_0 \)) of vibration. Therefore, the use of LDR, which strongly intensifies local vibrations, is beneficial for enhancing the efficiency of ultrasonic thermography. In the experiments, the effect of LDR on thermal response of defects was studied for circular FBH of different sizes in PMMA plates as well as for realistic defects in composites. Unlike traditional ultrasonic thermography experiments, which usually apply hand-pressed horn-type transducers for exciting high-power vibrations, we used conventional disk-like piezo-ceramic transducers attached (glued) to the specimen surface. The input voltage up to 90 V amplitude from HP 33120A function generator (bandwidth up to 15 MHz) via a high voltage amplifier.
HVA 3/450 was applied to the transducers to excite the flexural waves in the frequency band up to 100 kHz. The standing wave amplitudes were monitored with scanning laser vibrometer to evaluate a total acoustic power injected in the specimens; it was found to be in the sub-watt range even for maximum input voltage. The thermal response of the defects was visualized and measured with an IR-camera (IRCAM Equus 327K, sensitivity \( \approx 20 \) mK).

Fig. 7, left shows an example of thermosonic image for a circular FBH (radius 1 cm) excited at LDR frequency (11 kHz); the dynamics of the FBH thermal response is illustrated in Fig. 7, right. A quadratic dependence on the input amplitude agrees fully with theoretical expectations according to (1). The data also reveal a high efficiency of the vibro-thermal conversion: at 80 V input (0.2 W acoustic power) and 15s-ultrasonic exposure, the temperature rise in the FBH amounts to \( \approx 3 \)K. According to Fig. 7, the thermal response stays substantially beyond the camera sensitivity down to 15-20 V input (\( \approx 10 \) mW power).

A crucial contribution of the LDR to the heating effect is clarified by measurements of the temperature rise as a function of driving frequency (Fig. 8, experimental points). Even a 2-3% detuning from an exact LDR frequency drops the temperature down to basically non-measurable values of 10-20 mK and reduces the conversion efficiency by about two orders of magnitude. Such a high-Q thermal response is a consequence of the nonlinearity involved in the acousto-thermal conversion. This fact is illustrated in Fig. 8 by a close fit between the LDR frequency response of the FBH (shown in Fig. 1) squared and its thermal response.

![Thermosonic image of a circular FBH](image)

Fig. 7: Left - thermosonic image of a circular FBH (radius 1 cm) in PMMA plate at LDR frequency (11 kHz). Insonation time 15 s; input voltage of the transducer (top) 80 V; Right - temperature variation of a FBH at LDR as a function of input voltage of ultrasonic transducer.

To proceed to realistic defects we studied the effect of LDR on the thermal response for an in-plane oval delamination in a GFRP plate. The results are presented in Figs. 9, 10, where the thermal responses to a 2s-pulse acoustic excitation of the delamination are visualized (Fig. 9) and measured (Fig. 10) for the same input amplitudes (50 V) but different frequencies.

The thermographic image of the defect taken in the vicinity of the LDR \( \sim 20.9 \) kHz (Fig. 9 (b)) demonstrates that the heating is mainly produced in the core part of the delamination where maximum vibration amplitude is observed (Fig. 9 (a)). The temperature variation in this area (for insonation time 2 s) (Fig. 10) confirms the resonance character of the effect: At the LDR central frequency, the temperature rise (0.85 \( ^\circ \)C) is almost an order of magnitude higher than that outside the LDR bandwidth. For larger deviation of the driving frequency from LDR (including the specimen natural frequencies), the thermal response of the defect was barely measurable with the IR-camera (sensitivity \( \approx 20 \) mK).
5. Conclusions

A laser scanning methodology was successfully applied to provide the experimental evidence of the LDR in a variety of materials. For simulated and realistic defects (FBH, delaminations, cracks, impacts, etc.) the LDR-induced local resonance “amplification” of the vibration

![Fig. 9: Resonance imaging of an oval delamination in GFRP specimen: 20.9 kHz-LDR vibrometer (a) and IR-(b) images; (c) is IR-image at the specimen natural frequency 6.8 kHz.]

![Fig. 10: Thermal 2s-pulse responses of delamination at LDR-frequency (20900 Hz) and outside the LDR bandwidth (19000 Hz).]

![Fig. 8: Comparison between FBH vibro-thermography response and LDR acoustic frequency response (shown in Fig. 1) squared.]

amplitude averages up to ~ (20-40 dB). Since LDR is an efficient resonant “amplifier” of the local vibrations, it manifests a profound nonlinearity even at moderate ultrasonic excitation level. Besides a strong higher harmonic response, a high quality factor of LDR can also be used as a “linear” filter/amplifier in the frequency mixing nonlinear NDT. Since the acoustic dissipated power is proportional to the square of the amplitude of vibration, the use of LDR is beneficial for enhancing the efficiency and sensitivity of ultrasonic thermography. Unlike traditional thermosonic experiments, the LDR-thermography requires substantially lower acoustic power to activate defects that makes it possible to use conventional ultrasonic NDT instrumentation. For input acoustic power well below 1 W, the temperature rise about few K is normally measured for LDR of delaminations in composite materials. The use of LDR enables to enhance the acousto-thermal conversion efficiency by more than an order of magnitude.

6. Acknowledgement

The author acknowledges support of this study by EU FP-7 in the framework of ALAMSA project.

7. References