Highly-efficient and noncontact vibro-thermography via local defect resonance

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Abstract

A frequency match between the driving ultrasonic wave and characteristic frequency of a defect provides an efficient energy pumping from the wave directly into the defect (Local Defect Resonance (LDR)). Due to a strong resonance amplification of the local vibrations, the LDR-driven defects exhibit a high-Q thermal response and enable to implement frequency-selective thermosonic imaging with an opportunity to distinguish between different defects by changing the driving frequency. The LDR-thermosonics requires much lower acoustic power to activate defects that makes it possible to avoid high-power ultrasonic instrumentation and even proceed to a remote ultrasonic thermography by using air-coupled ultrasonic excitation.

1. Introduction

Ultrasonic based methodologies are among the leaders in the number and areas of NDT applications, not least because of simple and reliable ultrasound generation techniques as well as relatively inexpensive low-power electronics involved. On the contrary, ultrasonic thermography (vibrothermography, thermosonics) stands apart from other ultrasonic NDT counterparts for their specific instrumentation. To provide a measurable temperature response, thermosonics traditionally relies on high-power ultrasonic welding equipment, 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. The reason for this "specificity" is concerned with a low efficiency of ultrasound-heat conversion that is usually taken for granted without an effort to be optimized.

To make ultrasonic thermography compatible with conventional ultrasonic equipment would be a step on the way to extend its applicability in nondestructive inspection. To this end, an obvious task is to find out a feasibility of ultrasonic thermography in mW-acoustic power range typical for commercial ultrasonic applications.

In this paper, the solution is proposed by optimizing the ultrasonic excitation of defects via the concept of Local Defect Resonance (LDR) [2]. The LDR provides a selective excitation of a defect area and results in an efficient energy pumping from the wave directly into the defect strongly increasing its vibration amplitude. To evaluate the efficiency of heat generation by the LDR vibration pattern, the damping model is then applied to thermosonics of simulated defects (Flat-Bottomed Holes (FBH)). Both the calculations and experimental results confirm that thermal output within 1K is feasible for inputs in the range of a few acoustic mW. By combining LDR with lock-in approach reliable thermosonic imaging is expected to advance in sub-mW range of inputs. This opens an opportunity for noncontact thermosonic imaging to be implemented by using air-coupled ultrasound.

2. LDR concept

The concept of LDR is based on the fact that inclusion of a defect leads to a local decrease in stiffness for a certain mass of the material in this area, which should manifest in a particular characteristic frequency of the defect. The LDR fundamental frequency can be introduced as a natural frequency of the defect with an effective rigidity K_{eff} and

mass M_{eff} : $f_0 = \frac{1}{2\pi} \sqrt{K_{eff} / M_{eff}}$. To derive the expressions for K_{eff} and M_{eff} one could evaluate potential and

kinetic vibration energy of the defect. This approach applied to a circular FBH (radius R, thickness h) yields [3]:

$$K_{eff} = 192\pi D / R^2; M_{eff} = 1.8m,$$
 (1)

where $D = Eh^3 / 12(1 - v^2)$ is the bending stiffness and *m* is the mass of the plate in the bottom of the defect. Equations (1) are then combined to yield the LDR frequency for the circular FBH:

 $f_{\circ} \approx \frac{1.6h}{E}$

$$f_0 \approx \frac{1.6h}{R^2} \sqrt{\frac{E}{12\rho(1-\nu^2)}} \,. \tag{2}$$

The phenomenology presented is a simplified approach, which nonetheless enables to clarify the physical nature of the LDR. The expression for f_0 obtained above is applicable to evaluation of the fundamental resonance frequencies of the defects, like FBH as well as laminar defects in rolled sheet metals and delaminations in composites.

The problem in practical use of the analytical approach is concerned with the boundary conditions for the defect edges, which were assumed to be clamped in deriving Eq. (2). This is apparently justifiable for "deep" defects in plates, however, in a general case the analytical formulation presented above becomes problematic. Instead, a finite element (FEM) simulation was used to visualize the LDR vibration patterns and to evaluate the LDR frequencies.

The software COMSOL MULTIPHYSICS (physics package "structural dynamics," "eigenfrequency analysis") was found to be suitable for analyzing the vibration characteristics of structures with defects and to determine the LDR frequencies. By using eigenfrequency analysis of the model, each possible resonance of vibrations in the plate can be found and the vibration patterns plotted. Figure 1 (a) illustrates the vibration pattern at one of the specimen eigenfrequencies of 1.5 kHz. For a higher resonance frequency 10.4 kHz, a fundamental local resonance of a circular FBH is readily recognized (Figure 1(b)), followed by the higher-order LDR at the higher driving frequency of 23.25 kHz (Figure 1(c)).



Fig. 1. FEM simulations of vibration patterns of a PMMA plate (thickness 3 mm) with a FBH (radius 1 cm, depth 2 mm): 1.5 kHz plate eigenfrequency (a); fundamental LDR (10.4 kHz) (b), and higher-order LDR (23.25 kHz) (c).

3. 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 the vibration spectrum of every point of the specimen. The origin of each maximum is then verified by imaging the vibration pattern at the corresponding frequency.

Figure 2 shows an example of the LDR frequency response (a) and the vibration pattern (b) measured for a FBH in a PMMA plate. A strong enhancement (about 20 dB) of the vibration amplitude with a high Q-factor ($Q \approx 70$) observed locally in the defect area is identified as a fundamental defect resonance (Figures 2 a, b). Such a methodology was successfully applied to a search for LDR in a variety of materials [3]. The two other examples presented in Figures 2 (c) & (d) illustrate a clear evidence of LDR excited by propagating flexural waves in high kHz-frequency range for a simulated delamination (LDR frequency 91160 Hz) and an impact damage (LDR ~110000Hz) in carbon fiber reinforced plastic (CFRP). 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.



Fig. 2. Frequency response (a) and vibration pattern for FBH in a PMMA specimen (b); 91160 Hz LDR of a delamination (c), and 110 kHz LDR for an impact damage (d) in CFRP specimens.

4. Heat generation by LDR vibrations

In ultrasonic thermography, the defect thermal response is caused by a local dissipation of mechanical energy, which is converted into heat. For viscoelastic materials, this process is described by introducing the internal friction stress proportional to the velocity of strain variation that leads to a complex material elasticity $E = E_1 + jE_2$ with imaginary part responsible for material dissipation. For low loss materials $E_2 << E_1$, the dissipation module $E_2 \approx \eta E$, where η is the material loss factor. The complex material stiffness brings about a hysteretic stress-strain dependence (hysteretic damping model) with an area of the ellipse $\Delta W = \pi \varepsilon_0^2 E_2$ equal to the energy damping in a unit volume of the material per a cycle of vibration. The number of cycles per second is $\omega/2\pi$, so that the heat energy generated per unit time (heat power) is:

$$P_{H} = \frac{\Delta W}{\Delta t} = \frac{\omega \varepsilon_{0}^{2} \eta E}{2} \quad . \tag{3}$$

According to (3), the heat power generated is proportional to the frequency (ω) and the square of the strain amplitude (\mathcal{E}_0) of vibration. Therefore, the use of LDR, which strongly intensifies local vibrations, is beneficial for enhancing the efficiency of ultrasonic thermography.



It is instructive to note, that the polarization of the vibration is not worked out in the hysteretic damping approach. Note thereto that the high amplitude vibrations developed by LDR are polarized predominantly out-of-plane and therefore are readily detected by laser vibrometry as shown in Figures 2. The heat generation mechanism is concerned with internal friction, which is expected to be related to the in-plane vibration components. The evidence that the out-of-plane component of vibration is not directly involved in local heat generation is seen by comparing the LDR pattern for a FBH and the temperature induced pattern in the same defect (Fig. 3). A smooth "bell-like" LDR vibration profile inside the circular FBH (Fig. 2 (b)) generates a strong local heating in the centre surrounded by a temperature rise ring along the circumference (Fig. 3).

The out-of-plane displacement (U(r)) is nonetheless accompanied by the

in-plane extension-compression deformation (\mathcal{E}_r): it is zero in the middle plane of the plate and reaches maximal values on its both surfaces [4]:

$$\varepsilon_r = (d/2)(\partial^2 U(r)/\partial r^2), \qquad (4)$$

where d is the thickness of the plate.

For a fundamental resonance, the radial distribution of U(r) in a circular FBH (radius R) is given in [5]:

$$U(r) = \sum_{n=2}^{\infty} a_n (1 - (r/R)^2)^n .$$
(5)

Figure 4 shows that a close agreement between the calculations from (5) and the normalized LDR profile measurements are obtained by keeping only two terms in (5) and $a_3 = 2a_2$.

By substituting (5) in (4) the normalized radial distribution of the in-plane strain is calculated. Under assumption of the internal friction and the hysteretic damping approach (eq. (3)), the temperature profile and a local temperature rise generated by LDR vibrations can then be found by squaring the in-plane strain distribution. To this end, for a given vibration amplitude U(0) (measured by laser vibrometry) the absolute values of a_2 and a_3 are found from (5) and then used in calculating ε_r in (4). The values obtained are substituted in (3) to determine the heat energy generated in the defect and thus the temperature rise ΔT in the defect over a certain insonation time t:

$$\Delta T = \frac{\omega \varepsilon_r^2 \eta E t}{2\rho c_H},\tag{6}$$

where E is Young's modulus, ρ is the mass density and c_H is the specific heat of the material.

The calculations of the temperature profile inside a circular FBH (LDR frequency 12480 Hz) in PMMA carried out from (4)-(6) for the following experimental parameters: R = 1 cm; d = 1 mm; t = 10 s; $U(0) = 8 \cdot 10^{-7}$; E = 4.8 GPa; $\eta = 0.02$ are shown in Figure 5 and compared with the experimental data (see Fig. 3). A very close fit between the calculations and the results of measurements confirm a validity of the approach developed.

Fig. 3. Temperature pattern generated by LDR vibrations in a circular FBH.



Fig. 4. Profiles of LDR vibration pattern measured by laser vibrometry and calculated from eq. (5).



Fig. 5. Temperature patterns generated by LDR vibrations in a circular FBH: measured and calculated from eq. (6).

5. Efficiency of acousto-thermal conversion and feasibility of mW-LDR-thermosonics

According to eq. (6), to enhance efficiency of vibrothermography one should increase the local in-plane strain \mathcal{E}_r in the defect area. A traditional way to tackle the problem, is to increase the input acoustic power used for excitation of the defect vibrations. Instead, in the LDR based thermosonics a local increase in \mathcal{E}_r is due to resonant "amplification" of local defect vibrations achievable for a comparatively low input acoustic power P_{ac} . To quantify the benefit of LDR and to estimate realistic values of P_{ac} for a measurable temperature response, we introduce the LDR amplitude enhancement factor $K = U_{LDR} / U_{IN}$ as the ratio of out-of-plane vibration amplitudes inside and outside LDR.

It is physically clear that in a general case, the increase in U_{LDR} (or K) results in extra-bending and stronger extension-compression inside the LDR area and therefore cause an increase of the in-plane strain. This conclusion is readily seen for a FBH by combining (4) and (5) for a circular FBH to yield:

$$\varepsilon_r = 8U_{LDR}d/3R^2 \quad . \tag{7}$$

The excitation source is now introduced via its input acoustic power:

$$P_{ac} = \rho \omega^2 U_{IN}^2 cS/2 \quad , \tag{8}$$

where c is the acoustic wave velocity and S is the cross section area of the plate-like specimen.

By combining (7) and (8) the in-plane strain as a function P_{ac} is found and after substituting in (6) the temperature variation induced by LDR vibrations is obtained:

$$\Delta T = \frac{64K^2 d^2 \eta E t}{9\rho^2 c_H c S \omega R^4} P_{ac}.$$
(9)

Note, that for deriving (9) the expression for plane wave acoustic power (8) was used. Eq. (9) is therefore directly applicable to elongated plate-like specimens with the wave propagation in a single direction; for omni-directional propagation (large specimens) cylindrical wave intensity (P_{ac}/S) should be used.

In experiments, the effect of LDR on thermal response of defects was studied for a set of circular FBH of different sizes and LDR frequencies in PMMA plates. Unlike traditional thermosonic experiments, we used conventional disk-like piezoceramic transducers attached (glued) to the specimen surface. The input voltage up to 90V amplitude from HP 33120A function generator via a voltage amplifier HVA 3/450 was applied to the transducers to excite flexural waves in the frequency band up to 150 kHz. The wave amplitudes and velocities were monitored with a scanning laser vibrometer (vibration velocity mode) to evaluate a total acoustic power injected in the specimens. The thermal response of the defects was visualized and measured with an IR-camera (IRCAM Equus 327K, NETD \approx 15-20 mK).

Fig. 6 shows the dynamics of the FBH LDR-thermal response: an accurate linear dependence on the input acoustic power agrees fully with theoretical expectations of eq. (3). The data also reveal an extremely high efficiency of the vibrothermal conversion: at ~200 mW input and 15 s-ultrasonic exposure, the temperature rise in the central part of the FBH amounts to \approx 3 K. To quantify the LDR-enhanced acousto-thermal conversion efficiency introduced as

 $N = P_Q / P_{ac}$, the power required for such heating is calculated as $P_Q \approx 5 \times 10^{-3}$ W and for radiated acoustic power $P_{ac} \approx 200$ mW their ratio yields: $N \approx 2.5\%$.

A crucial contribution of the LDR to the heating effect is clarified by measurements of the temperature rise in the defect area as a function of driving frequency (Fig. 6). Even a slight (2-3%) detuning from an exact LDR frequency brings the temperature down to a basically non-measurable level of 10-20 mK and reduces the conversion efficiency by two orders of magnitude down to (1-2) $\times 10^{-4}$. Such a high-Q thermal response is a consequence of the quadratic nonlinearity involved in the acousto-thermal conversion (eq. (3)). This fact is illustrated in Fig. 6 by a close fit between the acoustic LDR frequency response of the FBH (shown in Fig. 2 (a)) squared and its measured thermal response.

The results of similar measurements obtained for other FBH in PMMA specimens are summarised in Table 1. The data reveal that for low-mW input acoustic power (ranged from 1.6 to 63 mW) the temperature rise in the defects is substantially beyond the noise level (ΔT between 50 to 460 mK) and is thus readily measurable. From (9), to compare and quantify the LDR contributions into thermal responses, the thermosonic quality factor of LDR is introduced as $Q = K^2 / \omega c$ and given in Table 1. For FBH of similar configurations, the Q factor is proportional to their thermal responses for unit input P_{ac} . The Q values are also used in Table 1 for estimation of ΔT from (9) for P_{ac} used in the experiments. For PMMA Young's modulus value E = 4.8 GPa (obtained by measuring longitudinal and shear wave velocities in the specimens) and typical variation of $\eta = (0.02 - 0.04)$ for PMMA [6], a reasonable fit between the calculations (within the range of η variation) and the experimental ΔT data is observed.

N	<i>K</i> ²	$\frac{K^2}{\omega c}$ (10 ⁻⁶)	$\begin{array}{c} P_{ac} \\ \text{measured} \\ \text{(mW)} \end{array}$	ΔT measured	ΔT calculated	$(P_{ac})_{\min}$ (mW) calculated
1	45.3	1.3	63	0.46 ± 0.02	0.26-0.52	3.9
2	377	9.9	4.6	0.14 ± 0.02	0.15-0.3	1
3	437	23.8	1.6	0.1±0.02	0.13-0.26	0.5
4	57.3	1.2	8.5	0.05 ± 0.02	0.03-0.064	5.1

Table 1. LDR thermosonics for FBH in 4 PMMA specimens: experimental vs calculated results.

According to Table 1, the most efficient LDR thermosonics is observed for specimen PMMA3 (FBH with the highest $K^2 = 437$) which exhibits a temperature rise of 0.1 K for only 1.6 mW of acoustic input. It is confirmed by the additional temperature measurement, which resulted in $\Delta T = 0.44$ K for $P_{ac} = 6.4$ mW, i.e. the LDR in this specimen is much more efficient heat producer than that in specimen 1. By introducing $\Delta T = 30$ mK as the lowest measurable thermal response, the minimum input P_{ac} can be evaluated from (9). The data in Table 1 confirm the feasibility of sub-mW LDR thermosonics for high Q defects (specimen 3).





Fig. 6. Temperature response of FBH as a function of input acoustic power at LDR frequency 11 kHz.

Fig. 7. Temperature and acoustic response squared for FBH as a function of driving frequency.

6. LDR thermosonic imaging

In this section, the enhancement of a defect thermal response by using the concept of LDR demonstrated above is



Fig. 8. Temperature response of a rectangular insert in CFRP plate at LDR frequency (8980 Hz, upper curve) and outside resonance (lower curve, 8000Hz). applied to thermosonic imaging of defects. Conventional ultrasonic piezo-ceramic transducers (Conrad Elektronik GmbH) were used for excitation of defects in the strip-like specimens of 10-20 cm length producing a quasi-plane wave field. In larger specimens, the defects were activated by using mobile vacuum attached transducers (SI Scientific Instr. GmbH) which generated cylindrical flexural waves. In all experiments, the acoustic power produced was monitored with a laser vibrometer and kept within mW-range.

Figures 8 & 9 show the results of LDR thermosonic imaging of a rectangular $(2x2 \text{ cm}^2)$ insert at 1.2 mm depth in $(300x300x5 \text{ mm}^3)$ CFRP specimen. Fig. 8 demonstrates a crucial role of LDR: At fundamental LDR frequency (8980 Hz) for 15 sec insonation and 80 V input, the temperature response (~0.25 K) is by more than an



Fig. 9. Laser vibrometry (a, b) and thermosonic (c, d) images of a rectangular insert in CFRP plate at fundamental LDR frequency (8980 Hz, (a, c)) and at higher-order LDR (15600Hz, (b, d)).

order of magnitude higher than that outside the defect resonance (8000 Hz). The laser vibrometry measurements reveal both the fundamental (Fig. 9, a; 8980 Hz) and the higher-order (Fig. 9, b; 15600 Hz) LDR with substantially different vibration patterns. The thermal images taken at the corresponding excitation frequencies (Fig. 9, c, d) demonstrate the importance of the higher-order resonances for visualization of the shape of the defect: while the fundamental LDR visualizes the center part, the higher-order LDR are responsible for imaging of the border areas of the defect.

Fig. 10 illustrates the application of the LDR thermosonics to an aluminum aviation component: (1.8x180x300 mm³) plate with a fatigue crack between the rivet holes (zoomed optical image fig. 10, a). The identification of LDR of cracks in metals is complicated due to high mechanical quality factors of the materials and various vibration modes of the cracked defects. One of the LDRs of the fatigue crack measured by laser vibrometry at 11600 Hz is shown in Fig. 10, b; the thermosonic image obtained at this frequency (Fig. 10, c) demonstrates the applicability of the LDR methodology to imaging of this kind of defects.



Fig. 10. Laser vibrometry (b) and LDR thermography (c) imaging of fatigue crack between the rivet holes (dotted area in zoomed optical image (a)) in aluminum aviation component.

Another example of LDR thermosonics in composites is given in Fig. 11 for a point-like impact damage (see Fig. 2, d) in a CFRP plate (270x40x1mm³). The acoustic frequency response of the defect (Fig. 11, a) reveals fundamental LDR around 110 kHz. Unlike a smooth LDR frequency response for a "solid" defect like FBH (Fig. 2, a), the resonance curve for impact damage displays ripples associated with resonances of weakly coupled parts of the defect. This effect is also evident in the thermal frequency response (Fig. 11, b).



Fig. 11. Acoustic (a) and thermal (b) LDR frequency responses of an impact induced damage in CFRP plate.

The temperature rise measured in Fig. 12, a) confirms highly efficient LDR thermosonics of impact damage in CFRP: $\Delta T = 1.4$ K for ~60 mW input acoustic power. Such a temperature variation provides an opportunity for reliable LDR thermosonic imaging in mW power range (Fig. 12, b) with a high temperature contrast in lateral direction (Fig. 12, a).





Fig. 12. LDR thermosonic imaging of ~(5x5 mm²) impact damage area in a CFRP plate (b); quantified temperature contrast of the image (a).

The results shown above imply that a strong increase in the defect temperature rise (thermal output signal) at LDR frequency enhances the signal-to-noise ratio (SNR) of thermosonic imaging. On the other hand, an increase of the SNR is also known to occur in the lock-in mode primarily due to diminishing the noise level [7]. By introducing the benefit of LDR in the lock-in approach a resonance thermosonic mode operating at unusually low excitation levels can be projected. To this end, following the general lock-in concept the amplitude of ultrasonic excitation at the LDR frequency was modulated sinusoidally by the lock-in frequency (between 0.01 Hz and 1 Hz). A temperature image sequence of the surface was recorded with the IR-camera and a discrete Fourier transformation at the lock-in-frequency was applied to compress this image sequence into a pair of amplitude and phase images.

An enhancement in sensitivity and the SNR of the LDR lock-in imaging are readily seen from Fig. 13, where the amplitude lock-in (a) and LDR temperature (b) thermosonic images of the FBH (specimen N3, Table 1) are shown. To have the SNR>1 in the temperature image (Fig. 13, b), the input power had to be increased up to ~2 mW (to generate $\Delta T \sim 100$ mK). On the contrary, the LDR lock-in image in Fig. 13, (a) was taken when the input was reduced to anomalously low power of ~ 200 μ W. The background for such an extraordinary performance is a combined action of the lock-in (reduction of noise) and the high thermosonic quality factor (efficient heat generation) in the LDR for this FBH (see Table 1).

In Fig. 14, a, b, the enhancement in sensitivity of thermosonics by combining LDR and lock-in is illustrated for an impact damage in a CFRP plate: the amplitude lock-in image (a) corresponds to ~1 mW input power while a similar contrast of the temperature image (b) requires ~16 mW of acoustic power.



Fig. 13. LDR thermosonic imaging of FBH in PMMA plate at LDR frequency 7670 Hz:. (a) - amplitude lock-in (lock-in frequency 0.05 Hz) image (acoustic input ~200 μ W); (b) – temperature image at input power ~ 2 mW.



Fig. 14. LDR thermosonic imaging of an impact (~5x5 mm²) in CFRP plate: amplitude lock-in image (a) at ~ 1mW input acoustic power; (b) – temperature image at ~16 mW input power.

7. LDR non-contact thermosonics

Such an efficient ultrasonic activation of defects enables to proceed with a remote thermosonic mode by using air-coupled ultrasonic (ACU) excitation. For this purpose, we used the Ultran ACU transducers whose fundamental frequencies (~50 and ~70 kHz) match the LDR frequencies of defects. The transducers were placed a few cm away from the defect area, while the IR-image was observed from the opposite side of the plate specimen (ACU-IR non-contact "through- transmission" mode) (Fig. 15, a). The AC-radiometer methodology [8] was employed to measure the ACU power (P_{ACU}) radiated.



Fig. 15. "Through-transmission" non-contact ACU thermosonics set-up (a); temperature response of FBH to 50 mW ACU excitation at LDR frequency 50.2 kHz (b).

The temperature response of a FBH in PMMA plate measured for input ACU power of ~50 mW and 30 s insonation pulse is shown in Fig. 15 (b): the temperature rise in the FBH area amounts to ~0.6 K that is far beyond the sensitivities of modern IR-cameras. The dynamics of ACU thermosonics is shown in Fig. 16 (a) and demonstrates that reliable defect detection is feasible for even lower ACU power (down to few mW).

The ACU thermosonic image of this FBH (3mm radius, 1mm thickness, 50.2 kHz LDR) in a PMMA plate (170x50x10 mm³) is shown in Fig. 16 (b). The data in Fig. 16 (a) were used to calculate the power (P_O) required for

heating the defect and to evaluate the efficiency of ACU thermosonics mode (averaged on the measurement points): $N_{ACU} = P_O / P_{ACU} \approx 0.8\%$.

An example of ACU imaging of realistic defects is illustrated in Fig. 17 for an impact damage (LDR frequency ~69.6 kHz) in 1.1 mm-thick multi-ply CFRP plate. To improve the sensitivity of thermosonics, the LDR excitation was combined with lock-in image processing. The ACU thermosonic phase images of the circular shape damage (radius ~12 mm) induced on the rear side of the impact are shown in Fig. 17 and taken in the lock-in mode for the input ACU power of ~7 mW. The laser vibrometry images are given in Fig. 17 for comparison. When the input ACU frequency matches exactly the LDR frequency (69.6 kHz), both the techniques reveal the total circular impact area reliably (Fig. 17, a, b). A minor mismatch between the excitation and the LDR frequencies (0.6 kHz) results in the contraction of both images with only the core part of the impact visible. The similarity in the frequency behaviour of the laser vibrometry and ACU LDR images confirms the practical relevance of non-contact ACU thermosonics.



Fig. 16. Temperature response of a circular FBH to ACU excitation (a); ACU LDR thermosonic image of a circular FBH in PMMA plate (b).



Fig. 17. Noncontact ACU LDR thermosonic (a, c) and laser vibrometry (b, d) imaging of an impact area (~12 mm diameter) in CFRP plate at different frequencies: a, b - ACU excitation at LDR frequency of 69.6 kHz; c, d – ACU frequency 69 kHz.

8. Conclusions

The bottleneck problem of ultrasonic thermography applications in NDT is a low efficiency of ultrasonic vibration-heat conversion, which is usually taken for granted without an effort to be optimized. In this paper, the solution proposed is based on optimizing a selective excitation of a defect area via the concept of Local Defect Resonance (LDR). Physically, the LDR concept is based on the fact that inclusion of a defect leads to a local drop of rigidity for a certain mass of the material in this area that should manifest in a particular characteristic frequency of the defect. A straightforward phenomenology and FEM-based calculations enable to evaluate the fundamental LDR frequencies of the defects, like FBH, and are also applicable to laminar defects in rolled sheet metals and delaminations in composites.

A direct way to experimentally reveal the 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. Such a 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 amplitude averages ~(20-40 dB).

In ultrasonic thermography, the defect thermal response is caused by a local dissipation of mechanical energy, which is converted into heat. For viscoelastic materials, this process is described by the hysteretic damping model, which shows that the heat power generated is proportional to the frequency and the square of the strain amplitude of vibration. Therefore, the use of LDR, which strongly intensifies local vibrations, is beneficial for enhancing the efficiency of vibro-thermography.

Polarization of the vibration is of much importance in the hysteretic damping approach. The high amplitude vibrations developed by LDR are polarized predominantly out-of-plane and therefore are not directly involved in local heat generation. The heat generation mechanism is concerned with internal friction, which is related to the in-plane vibration components. The out-of-plane vibration is nonetheless accompanied by the in-plane extension-compression deformation, whose distribution in the defect area determines the temperature profile generated.

To enhance the efficiency of vibro-thermography one should increase the local in-plane strain in the defect area. A traditional way to tackle the problem, is to increase the input acoustic power used for excitation of the defect vibrations. Instead, in the LDR based thermosonics, a local increase in the strain is due to resonant "amplification" of local defect vibrations (K) achievable for a comparatively low input acoustic power. The LDR contribution to the defect thermal

response is proportional to K^2 and can enhance the acousto-thermal conversion by one to two orders of magnitude.

In practical terms, it enables to advance to thermosonic imaging in a mW-acoustic power range tthat is typical for commercial ultrasonic applications. The case studies of LDR thermosonics for simulated and realistic defects (delaminations, impacts, cracks) in metals and composites confirm the feasibility of high contrast imaging in the mW-power range. Further enhancement of sensitivity and signal-to-noise ratio of thermosonic images is achieved by using LDR in the lock-in image processing mode.

An efficient ultrasonic activation of defects via LDR enables to proceed to remote thermosonic imaging by using an ACU excitation of defects. Direct temperature imaging LDR mode requires (10-100) mW ACU power while in a combination with lock-in reliable defect imaging is feasible for a few mW power input. The first experimental results confirm the practical relevance of non-contact thermosonic imaging in composite materials.

In summary, the application of LDR concept enhances substantially the efficiency of vibro-thermal conversion in ultrasonic thermography. The LDR thermosonics requires much lower acoustic power to activate defects that makes it possible to avoid high-power ultrasonic instrumentation and proceed to a non-contact imaging mode by using ACU excitation.

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