Local Defect Resonance as a Mechanism of Highly-Efficient and Frequency-Selective Ultrasonic Thermography

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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 due to a local defect resonance (LDR). The application of the concept of LDR is shown to enhance substantially the efficiency of vibro-thermal conversion in ultrasonic thermography. The resonance modes of ultrasonic thermography require much lower acoustic power to activate defects that makes it possible to avoid high-power ultrasonic instrumentation and proceed to a non-contact ultrasonic thermography version by using air-coupled ultrasonic excitation.

Keywords: Ultrasonic thermography, thermosonics, local defect resonance (LDR), non-contact ultrasonic thermography.

1. Introduction

Ultrasonic thermography (also called thermosonics) is a promising technique for nondestructive testing (NDT) of materials and industrial components based on the thermal response of defects exposed to ultrasonic excitation. However, heat generation by ultrasonic vibrations is managed by relatively inefficient processes of internal friction in the material and/or frictional rubbing at the defect interface. As a result, 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. To further intensify ultrasonic activation of defects the driving frequency is chosen to match one of the natural frequencies of the specimen or a quasi-chaotic acoustic excitation is produced by an intermittent horn-specimen contact to increase the vibration amplitude over a wide frequency spectrum [2].

In this paper, a new version of thermosonics, which uses the concept of Local Defect Resonance [3] (LDR), is proposed to enhance the efficiency and sensitivity of ultrasonic thermography. Unlike the resonance of the whole specimen, the LDR naturally provides an efficient energy pumping from the wave exclusively to the defect. The LDR thermosonics requires substantially lower acoustic power (down to a few mW) to activate defects that makes it possible to employ conventional ultrasonic NDT instrumentation and even proceed to a remote thermography mode by using air-coupled ultrasonic (ACU) excitation.

2. Acousto-thermal energy conversion

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 (Kelvin-Voigt materials), this process is described by introducing the internal friction force proportional to velocity of vibration in the expression for mechanical stress:

$$\sigma = E'\varepsilon + E''\ddot\varepsilon,$$  

(1)
where $\varepsilon$ is the strain, $E$ is a modulus of elasticity and $E^\prime\prime$ is the viscosity.

For $\varepsilon = \varepsilon_0 \sin \omega t$, from (1) $\sigma = E\varepsilon_0 \sin \omega t + E^\prime\prime \varepsilon_0 \cos \omega t$ so that the phase shift between strain and stress provides a hysteresis loop in the $\sigma - \varepsilon$ plane:

$$\sigma = \varepsilon_0 \sqrt{E^2 + \omega^2 E^\prime\prime^2} \sin(\omega t + \psi),$$

where $\tan \psi = \omega E^\prime\prime / E$.

The area of the loop (2) is found as $S = \pi \omega \varepsilon_0^2 E^\prime\prime$ and characterizes the mechanical energy dissipated in unit volume per period of vibration. Multiplying by frequency $\omega / 2\pi$ gives the expression for the energy loss per unit time:

$$\Delta W / \Delta t = \omega^2 \varepsilon_0^2 E^\prime\prime / 2.$$

According to (3), the dissipated power, which is primarily converted into heat, is proportional to the square of both the frequency and the amplitude of vibration. However, it is ill-advised simply to increase the frequency and amplitude in the ultrasonic source: that will result in heating of the whole specimen, while the local temperature rise in the defect area (and the contrast of its thermosonic image) can be provided only by some other heating mechanisms (interface rubbing of cracked defects, plastic deformation of asperities, etc.). An alternative approach is based on selective delivery of ultrasonic energy directly to the defect by using the concept of LDR.

3. The concept and evidence for LDR

3.1 LDR phenomenology

The LDR concept is based on the fact that inclusion of a defect leads to a local drop of stiffness for a certain mass of the material in this area, which should manifest in a particular characteristic frequency ($f_0$) of the defect. A fundamental LDR frequency can therefore be introduced as an eigenfrequency of the defect with an effective stiffness (rigidity) $K_{eff}$ and mass $M_{eff}$: $f_0 = \sqrt{K_{eff} / M_{eff}} / 2\pi$.

The expression for $K_{eff}$ can be derived by using the expression for potential energy of deformation for the defect: $W_{pot} = (K_{eff} U_{eff}^2) / 2$, where $U_{eff}$ is the effective vibration displacement in the defect area. We proceed with interpretation of the LDR concept for the defect presented as a circular flat-bottomed hole (FBH) of depth $d$ and radius $a$ in a plate of thickness $H$ excited by flexural vibrations in the plate, the case which simulates closely vibrations of such typical defects in composite plates as delaminations. If $d = H$, the boundary conditions for the vibrations of the residual part of the plate (a disk of thickness $h = H - d$) can be deemed as clamped (both the boundary displacement and its space derivative are zero). In this case, the displacement for the lowest mode of vibration $u(r) = u_0 (1 - r^2 / a^2)^2$ is used in the general expression for the potential energy of vibrations for a circular plate of thickness $h$ [4] to yield:

$$W_{pot} = 32\pi Du_0^2 / 3a^2,$$

where $D = Eh^3 / 12(1 - \nu^2)$ is the bending stiffness of the plate; $E$ and $\nu$ are Young’s modulus and Poisson ratio of the plate material.
The effective displacement is found as \( U_{\text{eff}} = u_0 / 3 \), so that for the effective rigidity of the defect one obtains:

\[
K_{\text{eff}} = 192\pi D / a^2.
\]  

(5)

The effective mass of the vibrating defect \( M_{\text{eff}} \) is introduced by writing its kinetic energy:

\[
W_{\text{kin}} = (M_{\text{eff}} U_{\text{eff}}^2) / 2
\]

(6)

and is calculated similarly as the general expression for the kinetic energy of a circular plate is known [4] to yield: \( M_{\text{eff}} = 1.8m \), where \( m = \pi \rho ha^2 \) is the mass of the plate in the bottom of the FBH; \( \rho \) is the mass density of the material.

The expressions for the effective rigidity and the effective mass of the vibrating defect are then combined to yield the LDR frequency for the FBH:

\[
f_0 \approx \frac{1.6h}{a^2} \sqrt{\frac{E}{12\rho(1 - \nu^2)}}.
\]  

(7)

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. In reality, the vibration field also comprises the higher-order modes; to calculate these eigen-frequencies a rigorous theory of plate vibrations should be used [4].

### 3.2 Experimental evidence for LDR

A direct way to experimentally reveal a local defect resonance 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 C-scan of the specimen surface. It enables to probe and indicate all possible resonances in every point of the specimen.

An example of application of such an approach is shown in Fig. 1 for an in-plane oval delamination (25x18 mm\(^2\)) in a glass fibre-reinforced composite (GFRP) plate (200x25x2.5 mm\(^3\)). A piezoelectric transducer attached to 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 (flat frequency response within 0-50 kHz (see inset in Fig. 1) or a wide-band chirp signal 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 (Polytec 3001S).

The origin of each maximum in Fig. 1 was verified by 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 10–18 kHz was found to be associated with the specimen width resonances. The specimen vibration pattern measured at 20.9 kHz – resonance (Fig. 2 (b)) reveals a strong enhancement (about 20 dB) of the vibration amplitude locally in the delamination area and is identified as a fundamental defect resonance.
Such a methodology was successfully applied by us to a search of the LDR in a variety of materials. The two examples presented in Figs. 3, a, b illustrate a clear evidence of LDR in kHz-frequency range for cracks and impacts in glass and carbon fibre-reinforced (GFRP and CFRP) composite and constructional (concrete) component. If a position of the defect is known, the LDR frequency response is readily obtained by a single-point spectral measurement in the defect area. 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 (delaminations, cracks, impacts, etc.) in high-Q materials (e.g. in CFRP).

![Figure 1](image)

Figure 1. Frequency response of a GFRP specimen with inter-ply delamination measured with a scanning laser vibrometer.

![Figures. 2, a, b. Vibration patterns at the GFRP specimen eigenfrequency (3.4 kHz, (a)) and the fundamental LDR frequency (20.9 kHz, (b)) of the delamination.](image)

![Figures. 3, a, b. LDR vibration patterns for a 50 µm-wide and 10cm-long crack in GFR-concrete specimen (frequency 4.19 kHz, (a)) and for an impact induced loss of fibres (area 25x2mm²) in a CFRP plate (frequency 3.66 kHz, (b)).](image)
4. LDR ultrasonic thermography

4.2 LDR thermosonics of simulated defects (FBH)

In the experiments, the effect of LDR on thermal response of defects was studied for a stack of circular FBH of different sizes and LDR frequencies in PMMA plates. 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 90V 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 50 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 ≈ 20 mK).

Fig. 4 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. 5. An accurate quadratic dependence on the input amplitude agrees fully with theoretical estimation according to (3). The data also reveal a high efficiency of the vibro-thermal conversion: at 80V input and 15s-ultrasonic exposure, the temperature rise in the FBH amounts to ≈ 3K. To proceed with quantification of the conversion efficiency we calculate the power required for such heating as: \( P_Q = 5 \times 10^{-3} \text{ W} \). The radiated acoustic power evaluated by measurements of the vibration amplitude was found to be: \( P_{ac} = 2 \times 10^{-1} \text{ W} \). The LDR-enhanced thermosonic conversion efficiency therefore is: \( N = P_Q / P_{ac} \approx 2.5\% \).

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. 6, experimental points). Even a slight (2-3%) detuning from an exact LDR frequency drops the temperature down to basically non-measurable level of 10-20 mK and reduces the conversion efficiency 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. This fact is illustrated in Fig. 6 by a close fit between the acoustic LDR frequency response of the FBH squared and its thermal response.

Figure 4. Thermosonic image of a circular FBH (radius 1cm) in PMMA plate at LDR frequency (11 kHz). Insonation time 15s; input voltage of the transducer (top) 80V.
A high thermal quality factor of the LDR enables to realize an advanced defect-selective imaging that combines a general selective defect imaging intrinsic to ultrasonic thermography with an opportunity to distinguish between different defects by changing the driving frequency. To demonstrate a feasibility of this mode we used a matrix of 16 FBH (\( a = 5\text{mm} \)) of different \( h / h \) (and corresponding LDR frequencies) in a disk-like PMMA specimen. As the excitation frequency changed, both the acoustic (with the scanning vibrometer) and the thermal responses of the defects were monitored. The images in Fig. 7 confirm that the defect positions synchronously “switch over” as soon as the driving frequency hits the LDR frequency of a particular FBH.

The results shown above imply that a strong increase in the defect temperature rise (thermal output signal) at LDR frequency enhances a high 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
ultrasonic thermography mode [5] primarily due to diminishing the noise level. 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 [5] the amplitude of ultrasonic excitation of the FBH at the LDR frequency (11 kHz) 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. 8, where the phase lock-in (left) and conventional temperature (right) vibrothermography images of the FBH are shown. Only $\approx 3$ mW of the input acoustic power used in this experiment appear to suffice for reliable LDR lock-in imaging (Fig. 8, left) but be too low for a conventional temperature image to develop noticeably even at the LDR condition.

4.3 LDR thermosonics of realistic defects

The benefits of applying LDR in ultrasonic thermography imaging are concerned with both of the two key factors (driving amplitude and frequency) that determine the thermal response of defects. The effect of the local increase in the vibration amplitude has been examined in the preceding section by using the FBH, which simulates closely such defects as delaminations.
To move on to realistic defects we studied the impact of LDR on the thermal response for an in-plane oval delamination in a GFRP plate, whose LDR was discussed earlier (Figure 1). 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 resonance frequency $\approx 20.9$ 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 2s) (Fig. 10) confirms the resonance character of the effect: At the LDR central frequency, the temperature rise ($0.85 \, ^{\circ}\text{C}$) 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 $\approx 20 \, \text{mK}$).

**4.4 Non-contact LDR thermosonics**

Such an efficient ultrasonic activation enables to proceed with a non-contact thermosonics mode by using an ACU excitation of defects. For this purpose, we used the Ultran ACU transducers whose fundamental frequencies ($\approx$50 and $\approx$70kHz) match the LDR frequencies of...
defects. The transducers were placed a few cm away from the defect area, while the IR-image was observed from the opposite side of the plate specimen (ACU-IR non-contact “through transmission” mode). The AC-radiometer methodology [6] was employed to measure the ACU power ($P_{ACU}$) radiated.

A temperature ACU thermosonic image of a FBH (3mm radius, 1mm thickness, 50kHz LDR) in a PMMA plate (170x50x10mm$^3$) is shown in Fig. 11 (a). For input ACU power of ~50mW and 30s insonation pulse, the temperature rise in the FBH area amounts to ~0.6K (Fig. 6 (b)) that is far beyond the sensitivities of modern IR-cameras. The data in Fig. 6 (b) were used to calculate the power ($P_Q$) required for heating the defect and to evaluate the efficiency of ACU thermosonic mode (averaged on the measurement points): $N_{ACU} = P_Q / P_{ACU} \approx 0.8\%$.

An example of ACU thermosonic imaging of realistic defects is illustrated in Fig. 12 for an impact damage (LDR frequency ~69.6kHz) in 1.1mm-thick multi-ply carbon fibre-reinforced plate. The ACU thermosonic phase image of the circular shape damage (radius ~12mm) induced on the rear side of the specimen (Fig. 12 (a)) is taken in the lock-in mode for the input ACU power of ~7mW. The similarity between the laser vibrometry (b) and ACU thermosonic (c) images confirms the practical relevance of this non-contact thermography mode.

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**Figures 11.** Temperature ACU thermosonic image of FBH (3mm radius, 1mm thickness) in PMMA plate (50kHz LDR excitation, 54mW ACU input power (a)); LDR induced temperature rise as a function of ACU power (b).

**Figures 12.** Imaging of impact-induced damage in multi-ply CFRP plate (photo, (a)); laser vibrometry image (b) and ACU-thermosonic lock-in phase image (modulation 0.03Hz, (c)) at LDR frequency 69.6kHz.
5. Conclusions

It has been demonstrated that the concept of a local mechanical resonance 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 manifests in a particular characteristic frequency of the defect. A straightforward phenomenology is proposed to evaluate the fundamental LDR frequencies of the defects, like FBH as well as laminar defects in rolled sheet metals and delaminations in composites.

Since the acoustic dissipated power is proportional to the square of the amplitude of vibration, the use of LDR, which strongly intensifies local vibrations, 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 1W, 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.

Due to quadratic nonlinearity involved in the acousto-thermal conversion, the LDR-thermography demonstrates a high-Q thermal response. A high thermal quality factor enables to realize an advanced defect-selective imaging that includes an opportunity to distinguish between different defects by changing the driving frequency. Another benefit of the LDR is concerned with an improvement of sensitivity and SNR by using the LDR-lock-in mode. A few mW of acoustic power was found to suffice for reliable LDR lock-in imaging but be too low for a conventional temperature imaging. An efficient ultrasonic activation due to LDR combined with lock-in enables to proceed with a non-contact thermosonics mode by using an ACU excitation of defects.

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References