LOCAL DEFECT RESONANCE FOR EFFICIENT DEFECT DETECTION IN COMPOSITES

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Keywords: non-destrutive testing, local defect resonance, vibrothermography, vibroshearography

Abstract
Ultrasonic wave-defect interaction, primarily, results in acoustic response of a defect which provides attenuation and scattering of ultrasound used as an indicator of defects in conventional ultrasonic NDT. The derivative ultrasonic-induced effects including nonlinear, thermal, acousto-optic, etc., are usually relatively inefficient so that the corresponding NDT techniques require an elevated acoustic power and stand out from conventional ultrasonic NDT counterparts for their specific instrumentation particularly adapted to high-power ultrasonic. In this paper we demonstrate how a frequency match between the driving ultrasonic wave and the characteristic frequency of a local defect area provides an efficient energy pumping from the wave directly into the defect. Due to a strong resonance amplification of the local vibrations, the LDR-driven defects exhibit a high-Q response in vibration and thermal output and enable to implement frequency-selective vibrothermography and vibroshearography imaging with an opportunity to distinguish between different defects by changing the driving frequency. The LDR-NDT requires much lower acoustic power to activate defects that makes it possible to avoid high-power ultrasonic instrumentation and produce fast defect-selective images.

1. Introduction

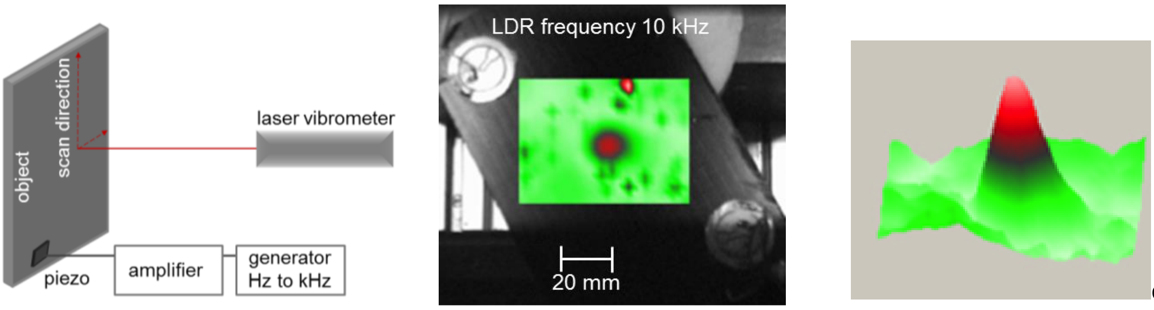
Ultrasound based methodologies are among the leaders in the number and areas of NDT applications, not least because of simple and reliable ultrasound generation techniques as well as relatively inexpensive low-power electronics involved. On the contrary, ultrasonic thermography (vibrothermography, thermosonics) and shearography stand apart from conventional NDT techniques due to specific high-power ultrasonic instrumentation required [1,2]. For instance, vibrothermography traditionally relies on high-power ultrasonic equipment, which was originally designed for the purpose of plastic welding and 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 (as well as ultrasonic shearography) compatible with conventional ultrasonic equipment would be a step on the way to extend their applicability in nondestructive inspection. To this end, an obvious task is to find out a feasibility of NDT with vibrothermography and shearography in mW-acoustic power range typical for commercial ultrasonic applications.
In this paper, the solution is proposed by optimizing ultrasonic excitation of defects via the concept of Local Defect Resonance (LDR) [3–5]. The LDR provides a selective excitation of a defect area and results in an efficient wave energy delivery directly into the defect strongly increasing its vibration amplitude. Such "targeting a defect" makes the LDR methodology different from Resonant Ultrasound

Excerpt from ISBN 978-3-00-053387-7

Spectroscopy (RUS) widely used in NDT [4]. RUS NDT deals with a resonance of the whole specimen and utilizes the deviation of the resonance pattern of a faulty part from that for a “perfect” (free from defects) similar component. On the contrary, LDR excitation is spatially defect-selective: A local increase in defect vibration amplitude enhances efficiency of any ultrasound activated NDT technique and is the way to a sensitive imaging of defects on the background of an intact part of material. Therefore, by using LDR in ultrasonic vibrometry, thermography and shearography, reliable and sensitive defect-selective imaging is expected to advance in low-power range of inputs.

2. Experimental procedures for detection of local defect resonances

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 (Figure 1 (a)). 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 1 (b) shows an example of the LDR vibration pattern measured for a 40 J impact in a CFRP plate. A strong enhancement of the vibration amplitude observed locally in the defect area is identified as a fundamental defect resonance (Figure 1 (c)). Such a methodology was successfully applied to a search for LDR in a variety of materials and components.



a) b) c)

Figure 1. (a) Schematic representation of the vibrometry measurement of LDR frequencies.

To identify the frequency range for a search of LDR an analytical approach developed in [5] for simple defects, like flat-bottomed holes (FBH) can be applied. The fundamental LDR frequency for a circular FBH (radius R, thickness h) (also applicable to circular delaminations) is determined as:

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

Here E is the material Young´s modulus, ρ the density and ν Poisson ratio.

While highly sensitive, vibrometry as a scanning method is comparatively slow in regards to defect imaging of large areas. Derivative ultrasonic-induced effects e.g. thermal and acousto-optic, are normally relatively inefficient so that the corresponding NDT techniques require an elevated acoustic power. Yet the high-Q amplification of local defect resonance vibrations allow the use of thermal and optical NDT techniques to produce high contrast defect images. Both thermographic and speckle pattern optical techniques are full-field camera based methods that allow for fast testing of large areas.
Shearography is related to vibrometry, because it’s a laser interferometric technique designed for measuring displacement on the nanometer scale. The use of ultrasonic excitation has long been known and employed [6,7] for defect imaging identifying the higher displacement of low-stiffness regions.
Thermographic NDT with ultrasonic excitation is a well-established NDT method investigated and developed over the last decades [1,2,8]. Usually high power systems are employes in order to provoke

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crack friction heating, but also visco-eleasting heating can be observed. It's an indirect method for observing vibrations, because the infrared camera monitors the specimen surface where heat spots may occur once the vibration amplitude is sufficient.

3. LDR testing of composite materials

This chapter will demonstrate the feasibility of the aforementioned techniques for several composite materials with defects.

3.1. Comparison of different imaging techniques

The effect and features of LDR NDT are demonstrated in Figure 2 for a realistic defect visualized with the techniques discussed above. The LDR imaging results are shown for a aluminum honeycomb structure (thickness 16 mm) with GFRP liners (0.5 x 100 x 100 mm^2, Figure 2 (a)) with several inclusions of resin and water. The ultrasonic excitation was carried out by conventional piezo-ceramic transducers attached to the rear side of the structure. The laser vibrometry scan of the front side (Figure 2 (b)) indicates LDR of one of the defects at 14940 Hz. The results of both shearographic and thermosonic imaging confirm substantial enhancement of the sensitivity of detection at the LDR frequency: The images practically disappear even at a minor frequency mismatch from the LDR frequency.

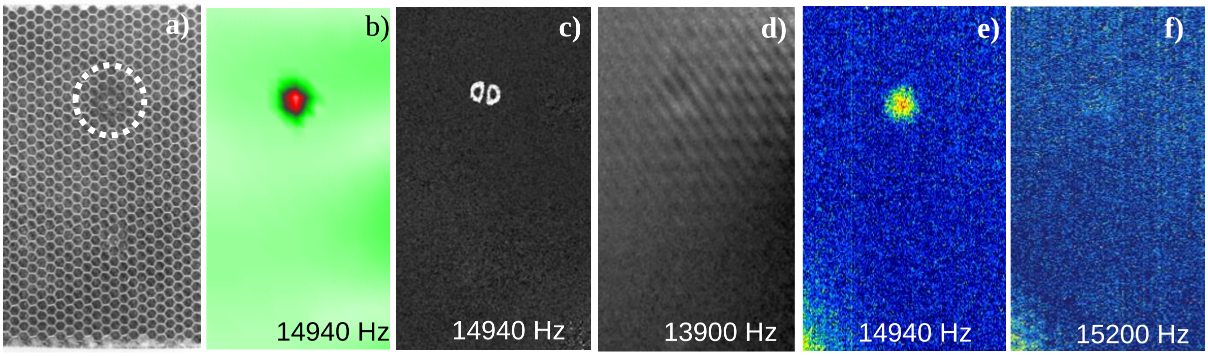

Figure 2. LDR vibrometry (b), shearography (c, d) and thermosonic (e, f) imaging of an adhesion lack area in honeycomb structure (a): The excitation frequencies are indicated on the images.

3.2. LDR shearographic imaging

To apply LDR ultrasonic shearography to imaging of defects we used a CFRP specimen with artificial sqaure delamination (PTFE inserts) shown in Figure 3 (a). A vacuum-attached shaker was applied for ultrasound excitation via an amplifier with electric power of about 20 W. In Figure 3 (c), the results of shearographic imaging are given along with a laser vibrometry image in Figure 3 (b).

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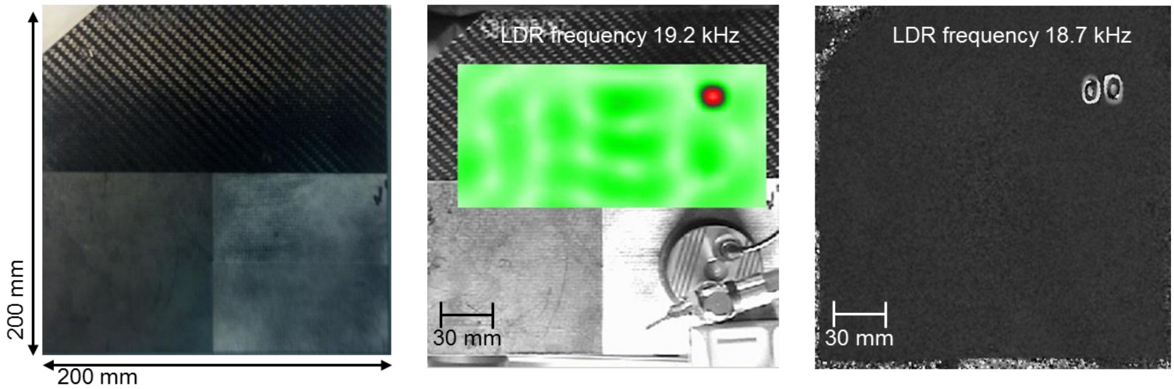
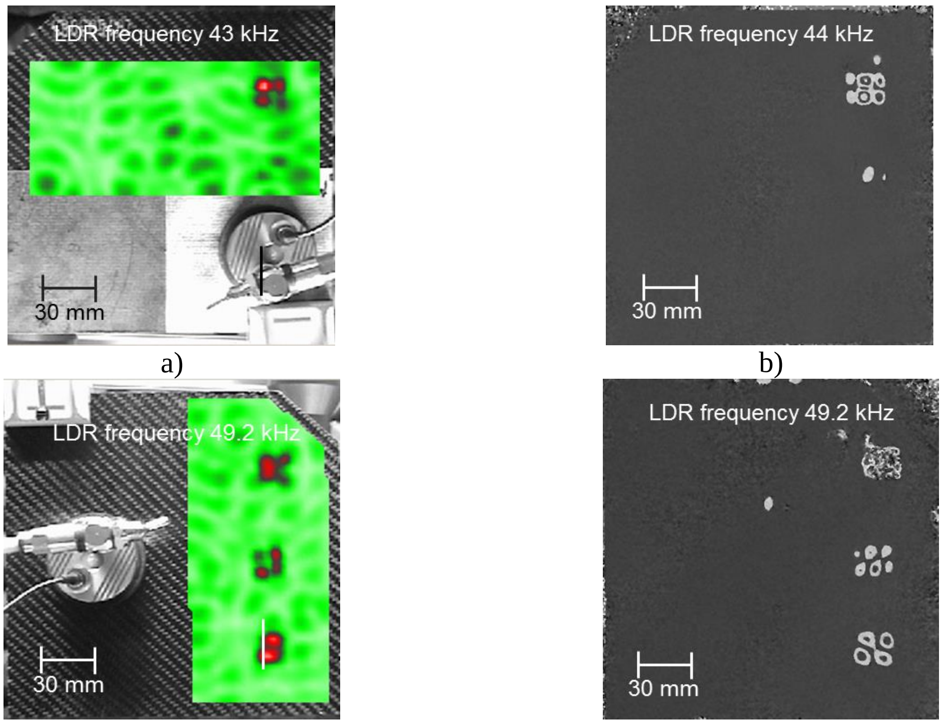


a) b) c)

Figure 3. CFRP sample (thickness 6.2 mm) with delaminations in different depth positions (a). LDR defect imaging by using laser vibrometry (b) and shearography (c). The optimum LDR frequencies are indicated in the images.

The comparison of both methods indicates a slight LDR frequency deviation (500 Hz) between fundamental LDR frequencies. The cause of the frequency deviation can be traced back to different positions of the excitation transducer. A similar minor difference between the higher-order LDR resonance frequencies is also seen in Figure 4 (a) and (b). Worthwhile noting that the higher-order LDR substantially better visualizes the quadratic shape of the defect. The same result is shown in Figure 4 (c) and (d) where shearography images – obtained at higher frequency (49.2 kHz) – visualize several delaminations simultaneously. One can clearly trace various order LDR shearographic patterns, which represent closely the true, square defect shape.



c) d)

Figure 4. Higher order laser vibrometry (a) and shearographic (b) imaging of a square delamination in CFRP. Simultaneous imaging of delaminations via higher-order LDR vibrometry (c) and LDR shearography (d).

2.2. Wideband thermographic imaging

Defect resonance frequencies are usually unknown and require substantial time to determine via wideband excited vibrometry even with analytical estimates in place beforehand. It is therefore necessary to find a method that makes use of the effect of LDR without knowledge of the specific frequency.

Experience shows that the frequencies searched for typically vary in a band up to 100 kHz. Depending on the material and even more so on the defect size this range can be reduced even further. It is therefore obvious to vary the excitation frequency continuously until a defect response is observed. For thermography that is until a temperature rise above the measurement threshold is found. This way one can roughly determine an LDR frequency with thermal imaging as is shown in Figure 5. The temperature is plotted over time and frequency, respectively, for a defect area in an aerospace composite part with impact damage. The excitation frequency was changed over a time range of 10 s from 30 kHz to 50 kHz. At approximately 43 kHz a significant temperature rise of about 20 mK is observed, while only providing 5 W electrical power to the shaker. A standard fourier transform evaluation of the temperature-time data for each camera pixel can be performed in order to reduce measurement noise and produce high signal-to-noise ratio results as shown in Figure 6.

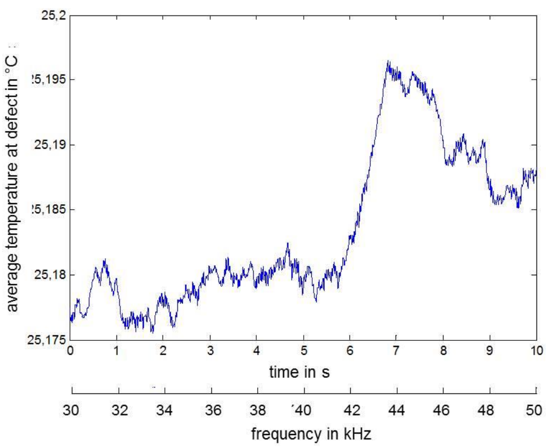


Figure 5. Temperature over time for frequency sweep excitation with a significant jump at LDR frequency 43 kHz

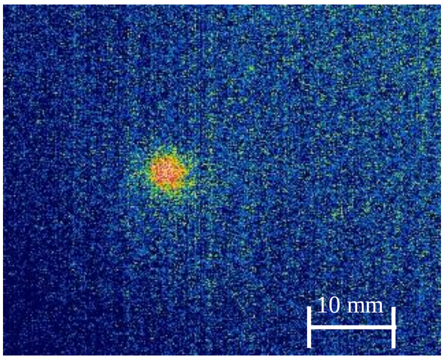


Figure 6. Fourier transform evaluation of the temperature data after 10 s sweep excitation

3. Conclusions

In summary, a frequency match between the excitation ultrasonic frequency and the frequency of LDR leads to substantial increase of the defect local vibration amplitude. It results in enhancement of sensitivity and efficiency in ultrasonic NDT and imaging of defects via laser vibrometry, vobrothermography and vibroshearography. A strong frequency selectivity of LDR brings an opportunity of detecting a certain defect among a multitude of others by using all above mentioned NDT methods. An improvement of image quality is obtained in the higher-order LDR and wide-band ultrasonic excitation modes. The LDR NDT can be employed without any knowledge of the material such as plybooks and requires much lower acoustic power to activate the defects than typical lab scale set-ups, while producing high signal-to-noise ratio results within few seconds. These advantages open up the possibility of mobile testing devices that can be used in rough areas.

Excerpt from ISBN 978-3-00-053387-7

Acknowledgments

One of the authors (Igor Solodov) acknowledges support of this study in the framework of ALAMSA project funded from the European Union's Seventh Framework Programme for research, technological development and demonstration under grant agreement no.314768.

References

[1] Zweschper T, Dillenz A, Riegert G, Scherling D, Busse G. Ultrasound excited thermography using frequency modulated elastic waves. Insight-Non-Destructive Testing and Condition Monitoring 2003;45(3):178–82.
[2] Han X, Favro LD, Thomas RL. Sonic IR imaging and vibration pattern studies of cracks in an engine disk. In: AIP Conference Proceedings. IOP INSTITUTE OF PHYSICS PUBLISHING LTD; 2003, p. 513–516.
[3] Solodov I, Rahammer M, Gulnizkij N. Highly-Sensitive and Frequency-Selective Imaging of Defects via Local Defect Resonance. The e-Journal of Nondestructive Testing 2014;19(12).
[4] Solodov I, Bai J, Busse G. Resonant ultrasound spectroscopy of defects: Case study of flat-bottomed holes. J. Appl. Phys. 2013;113(22):223512.
[5] Solodov I, Bai J, Bekgulyan S, Busse G. A local defect resonance to enhance acoustic wave-defect interaction in ultrasonic nondestructive evaluation. Applied Physics Letters 2011;99(21):211911.
[6] Menner P, Gerhard H, Busse G. Remote defect visualization with thermal phase angle shearography. In: Review of Progress in Quantitative Nondestructive Evaluation. AIP Publishing; 2010, p. 2068–2075.
[7] Steinchen W, Yang L. Digital shearography: theory and application of digital speckle pattern shearing interferometry. SPIE press Bellingham; 2003.
[8] Salerno A, Dillenz A, Wu D, Rantala J, Busse G. Progress in ultrasound lockin thermography. Quantitative infrared thermography, QIRT 1998;98:154–60.

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