Local Defect Resonance-based Shearography to Increase the Selectivity of Defects

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Abstract. The optically excited lock-in shearography (OLS) is an optical method for remote non-destructive testing by monitoring the displacement field of the object to be inspected. OLS is designed for quick and one-sided non-destructive testing of large components. The surface displacement is measured by means of an expanded laser beam. For non-destructive testing, usually not the displacement of the whole inspected object is of interest, but only the changes in the displacement field that are caused by defects. To determine the depth of defects we combined it, in the past, with the lockin technique where modulated excitation generates a thermal wave in the sample which is monitored by a shearography sensor. By using the optical excitation, in some cases, the defects signals are superimposed by the large displacement fields. Additionally, conventional application is often too long which makes the new approach with measuring times of about a few seconds a promising alternative. Thus, the elimination of these drawbacks will be helpful to broaden the range of applications of shearography. Non-destructive testing is an important part of the whole quality strategy of manufacturing and operation of CFRP components. However, routine application is often too long with regard to industrial inspection requirements. One possible solution to this problem is local defect resonance (LDR), a recently proposed method, which is combined in this paper with shearography. The LDR-based shearography (LDRS) measurements are performed within a few seconds. In practical use, the component is excited at frequencies in the range of 5-50 kHz and the component surface observed as live video. We report on achievable detection sensitivities when using the LDR and present testing results of different types of CFRP-components.

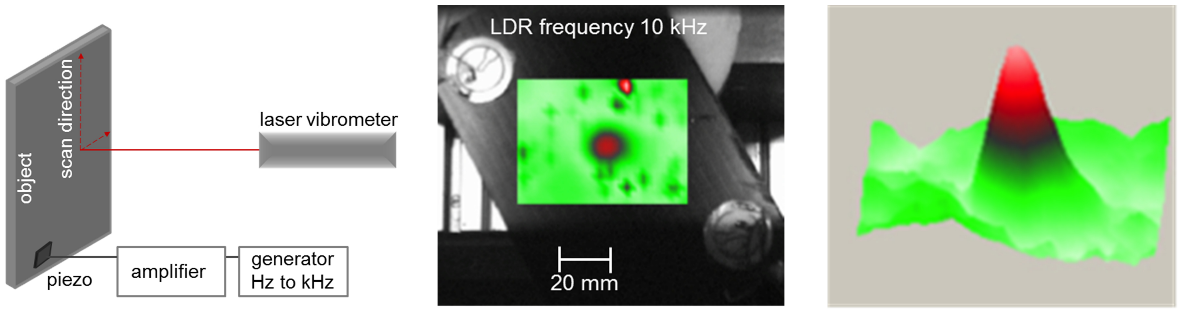
Introduction

Ultrasonic based methodologies are among the leaders in the number and areas of NDT applications, not at least because of simple and reliable ultrasound generation techniques as well as relatively inexpensive low-power electronics involved. On the contrary, ultrasound-activated shearography stands apart from conventional NDT techniques due to specific high-power ultrasonic instrumentation required [1]. In this paper, the solution to reduce the input power 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. By combining LDR with shearography, reliable and sensitive shearographic imaging is expected to advance to low-power range of inputs.

Detection of resonant acoustic nonlinearity of defects via vibrometry

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 (carbon fiber reinforced plastic) 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)

Fig. 1. (a) Schematic representation of the vibrometry measurement of LDR frequencies. LDR detection by laser vibrometry in a 40 J impact CFRP plate (the centre area of the image (b); enhancement of local vibration amplitude (c).

To identify the frequency range for a search of LDR an analytical approach developed in [3] for the defects, like flat-bottomed holes (FBH) can be applied. The fundamental LDR frequency for a circular FBH (radius R, thickness *h*) (also applicable to the cracked defects, like delaminations, etc.) is determined as:

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

where E is material Young´s modulus, ρ is the density and ν is the Poisson ratio. By using equation (1), the LDR fundamental frequencies can be estimated.

Methods for the detection of defects via shearography

All speckle-interferometrical methods use images of speckle patterns on the surface of a sample. The speckle pattern emerges on any optically rough surface by interference on the detector when it is illuminated with coherent light. The pattern correlates with the shape of the object surface and can therefore be used to determine the object deformation within a fraction of the laser wavelength. A CCD- or CMOS-camera combines the speckle pattern of at least two different object states (unloaded and loaded). The superposition of these images results in a fringe pattern that can be used to determine the out-of-plane deformation distribution.

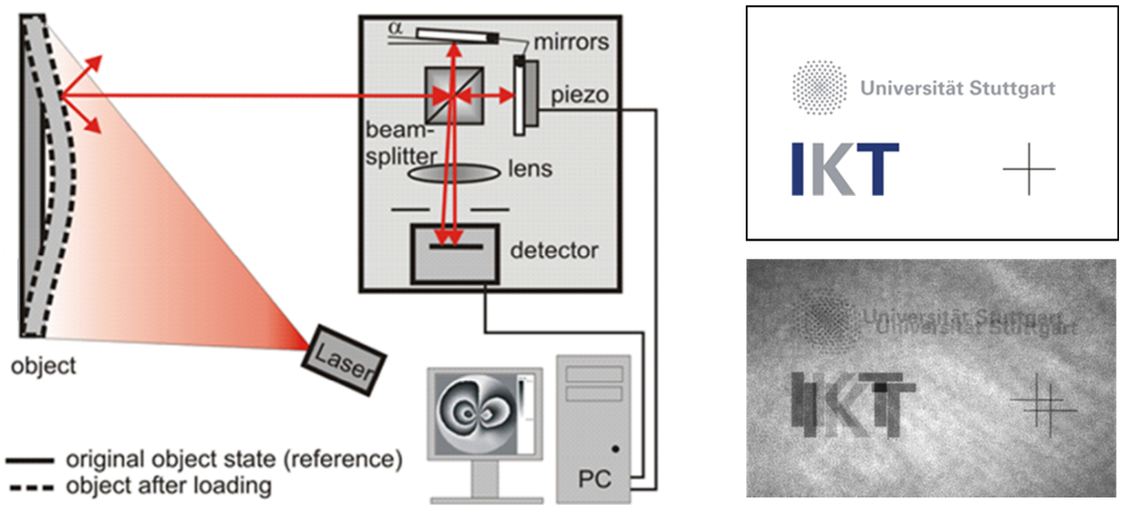


Fig. 2. Left: Sketch of the optical setup of the shearography sensor. Right, top: Example of an optical rough surface (business card). Right, bottom: Card illuminated by expanded laser light. The second speckle image of the tilted mirror is superimposed with the original speckle image of the object surface on the detector.

Shearography uses an internal reference beam: the scattered light from the object surface passes through a shearing element that consists of a beam splitter, cube, and two mirrors (Fig. 2.). One of the mirrors is tilted by a small angle, which results in an image duplication on the detector. Therefore, the light beam of an object point is superimposed with the light originating from an adjacent point on the surface. As a result, the derivative along the shearing direction is measured [4]. By phase shifting with a piezo-actuator and using filtering- and unwrapping algorithms, the contrast can be improved and evaluation of the surface deformation can be made.

Conventional excited shearography for fast detection of defects

In a conventional measurement, the object is statically loaded for a short time and a sequence of fringe patterns is recorded; the image with the best contrast is being evaluated, so most of the information contained in the sequence is lost. Additionally it suffers from responding to the deformation of the whole test object, which can hide defects.

Optical excited lockin shearography (OLS) for increasing the defect selectivity

Optically excited lockin shearography uses a shearography sensor, but with a dynamic excitation. By intensity modulation of halogen lamps, the object surface is heated periodically, thereby launching a thermal wave into the object. The shearography sensor continuously monitors the periodical object displacement which is caused by the thermal wave. As in conventional shearography, a sequence of images is recorded, but not after a short, static excitation, but during a modulated excitation, and in contrast to the conventional method, not only one fringe image is evaluated, but the whole sequence of images. After recording this image sequence the discrete Fourier transformation extracts the phase and the amplitude image of the recording images sequence. The lockin amplitude image (showing the local height of the modulation effect) and the lockin phase image, displaying the local thermal phase delay between excitation and object response.

The lockin shearography is less sensitive to vibration than other interferometrical methods (e.g. ESPI) and thus generally can be used in industrial environments. However, one has to consider that it is still time consuming which often hinders its use in high throughput serial inspection application.

The experimental setup of the lockin shearography system (Fig. 3.) consists of an array of laser diode modules that are mounted variably on four arms helping the object to be illuminated homogeneously. For thermal excitation, up to four lamps with filters can be used [5].

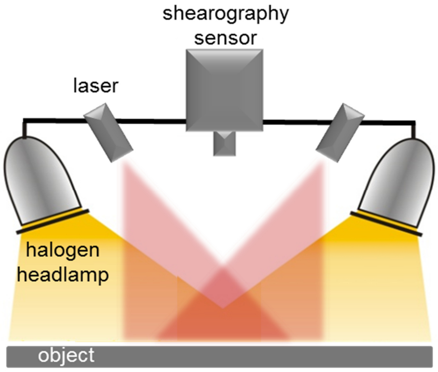


Fig. 3. Experimental setup of the optical excited lockin shearography.

Evaluation of LDR via shearography

Fig. 4 shows a scheme of experimental setup for LDRS. A wideband piezoelectric transducer was used for excitation of ultrasound in a specimen. For this purpose, a sweep input signal in the bandwidth 1-100 kHz from a voltage generator was applied to the transducer while the shearographic response was monitored with the shearographic sensor. The excitation frequency with a maximum shearographic response was identified as an LDR frequency for a defect in question.

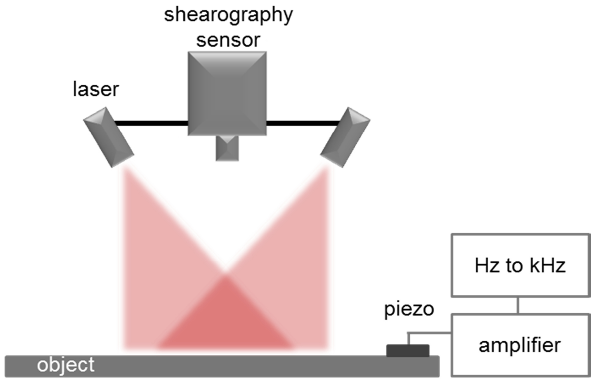


Fig. 4. Experimental setup of the ultrasound excited shearography. The ultrasound signal is coupled in the object by a piezo element which is attached to the object surface.

The ultrasound excited shearography uses a conventional shearography sensor with a continuous wave illumination. To evaluate LDR frequencies the shearographic response was first measured for a set of simulated defects (circular flat-bottomed hole (FBH)) in a PMMA plate. The diameters of all FBH were 20 mm and the residual wall thickness was varied between 0.85 mm to 2 mm. In Figure 5 a), the sketch of the PMMA plate is shown. In Figure 5 b), the results of LDR frequency measurements are shown and compared with calculations by using equation (1).

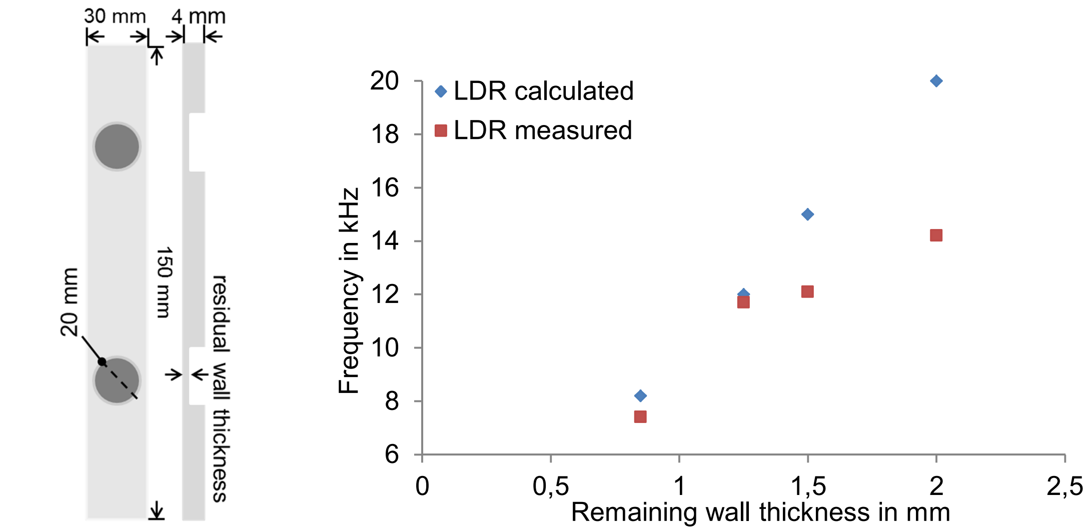
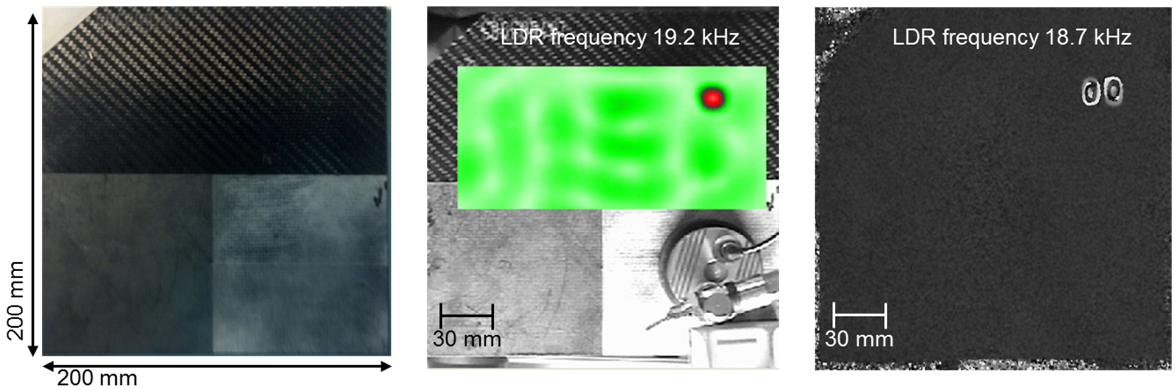


Fig. 5. (a) Sketch of a sample with FBH made out of PMMA. Comparison of shearographic measurements and calculations of LDR frequencies for a set of FBH with various residual wall thicknesses (b).

A reasonable overall agreement between experimental and calculated data is observed for FBH with a remaining wall thickness below about 1.2 mm.

LDR shearographic imaging

To apply LDR ultrasonic shearography (LDRS) to imaging of defects we used CFRP specimen with artificial delamination shown in Figure 6 (a). A vacuum-attached shaker was applied for ultrasound excitation via the amplifier with electric power of about 20 W. In Figure 6, the results of shearographic imaging are given along with laser vibrometry images.



a) b) c)

Fig. 6. 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 Figures 7 (a) and (b). Worthwhile noting that the higher-order LDR substantially better visualizes quadratic shape of the defect. The same result is shown in Figures 7 (c) and (d) where shearography images – obtained at higher frequency (49.2 kHz) – visualize a few delaminations simultaneously.

One can clearly trace various order LDR shearographic patterns, which represent closely the defect shape.

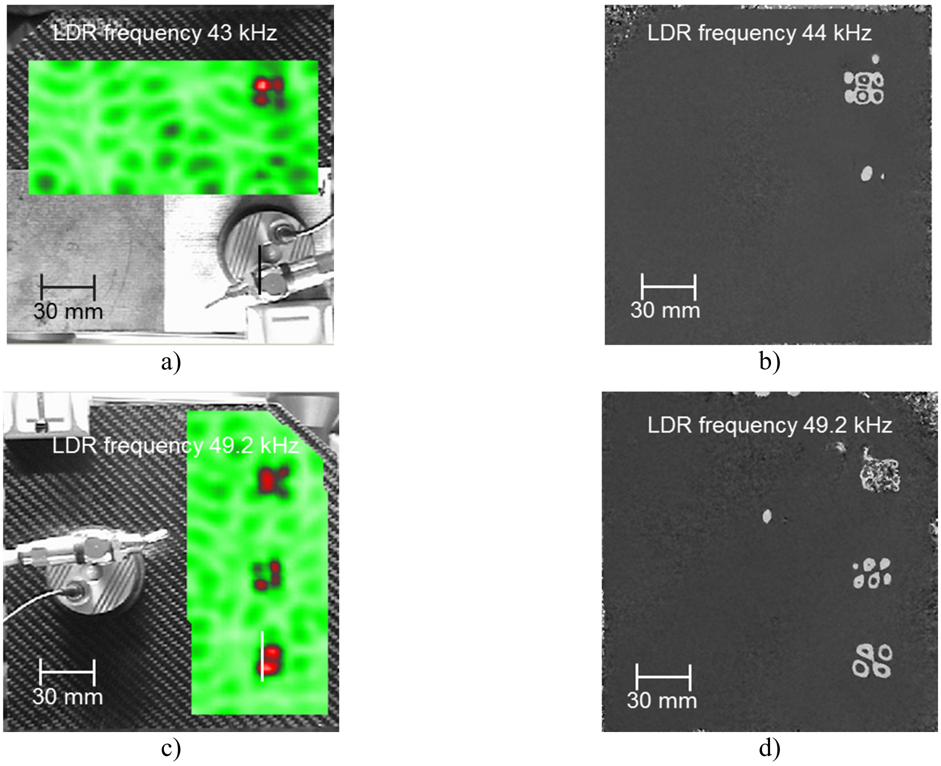


Fig. 7. Higher order laser vibrometry (a) and shearographic (b) imaging of a square delamination in CFRP. Simultaneous imaging of delaminations via higher-order LDR vibrometry (c) and LDR shearography (d).

LDR-enhanced signal-to-noise ratio (SNR)

To quantify the benefit of ultrasound-activated LDR shearography the SNR was evaluated for the case of optical and LDR ultrasonic defect imaging of a set of artificial delaminations (20 x 20 mm^2) in a sample made of CFRP (200 x 200 x 6.2 mm^3). Figure 8 shows the imaging results obtained for different excitation sources.

To estimate the quality of the images the SNR was measured in the image areas along the red line in Figure 8.

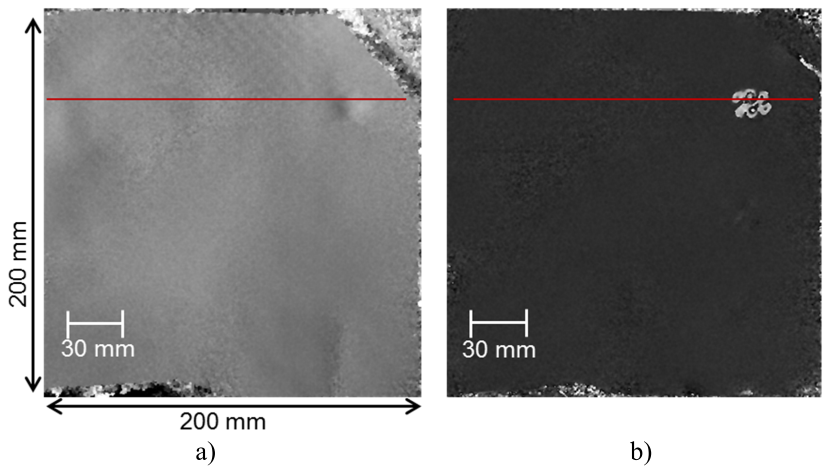


Fig. 8. Shearographic imaging of a delamination obtained with optical (a) and LDR (18.7 kHz) ultrasonic (b) excitation.

The contrast measurements shown in Fig. 9 demonstrate the benefit of LDR shearography: The signal to noise ratio can be enhanced by a factor of 10 to an absolute SNR-value of 30 when using LDRS mode.

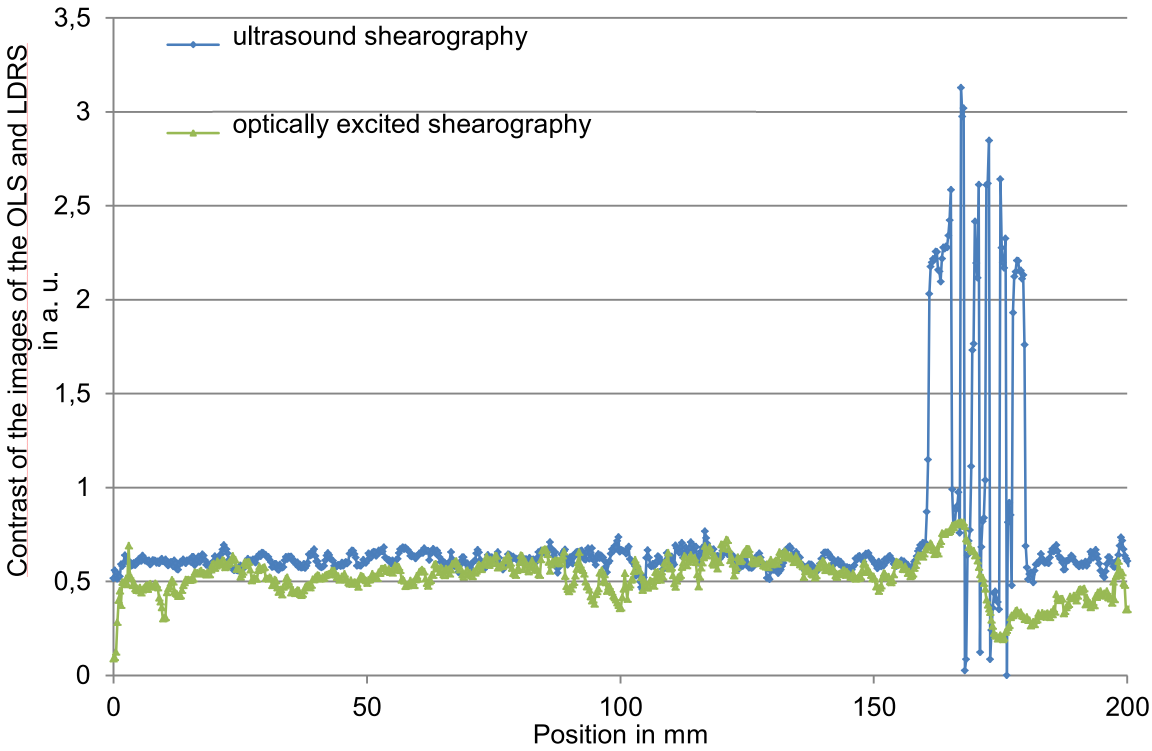
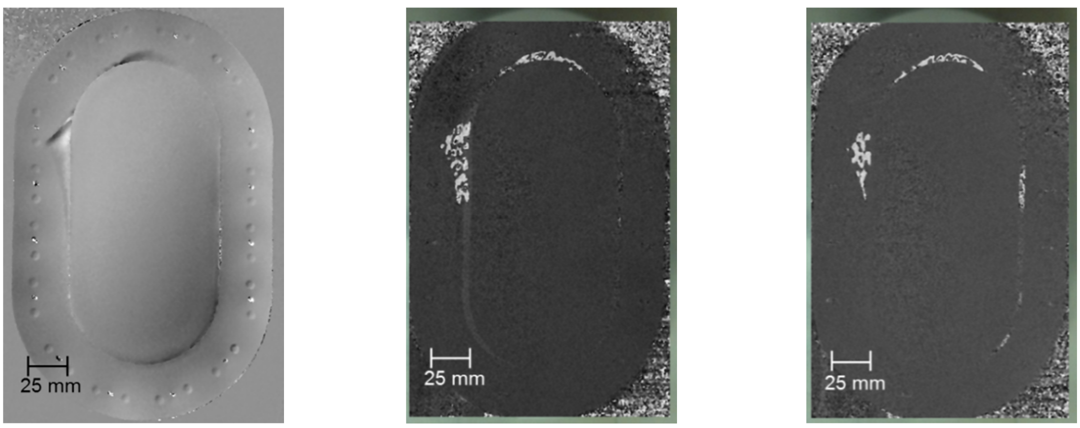


Fig. 9. Contrast of the images of the OLS and LDRS as a function of the position along the red line in Fig. 8.

Comparison between the LDRS and the OLS on real component application

The defect selectivity by frequency variation via LDRS is shown by testing a real aviation component (service door cover of an Airbus 330) for optical and LDR ultrasonic excitations. The results of both measurements are shown in Figure 10. The two delaminations in the upper part of the door are detected by both optical shearography and LDRS indicating LDR at the excitation frequency 30.2 kHz. A pair of new cracks which are not seen with optical shearography is detected in LDRS by changing the driving frequency to 43.3 kHz (Fig. 10 (right)).



a) b) c)

Fig. 10. Inspection of a service door (Airbus 330) the OLS in comparison with the modulated optical frequency of 0.01 Hz (a) and the LDRS with an excitation frequency of 30.2 kHz and with 43.3 kHz (c).

The comparison between the OLS and the LDRS reveals that by using LDRS both the inspection time can be reduced by a factor 10 and the energy input by a factor 5 [6].

Summary

Both laser vibrometry and shearography measurements demonstrate the resonant behaviour of defects which results in a strong increase of local defect vibrations. The shearographic response of ultrasound-activated defects is enhanced dramatically when the driving frequency matches the resonant frequency of the defect. The energy required for ultrasonic activation of defects in LDR-shearography mode can be reduced substantially in comparison to other excitation methods. The LDRS demonstrates enhancement in sensitivity, contrast and signal-to-noise ratio of the defect images. Furthermore, the testing time in LDRS mode reduces by a factor of 10 as compared to lockin optically excited shearography. The LDRS excites defects without excitation of the whole specimen and enables to increase the defect selectivity and to decrease the inspection times in comparison to the OLS.

References

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