DEFECT SELECTIVE NDE BASED ON THERMOGRAPHIC AND INTERFEROMETRIC MAPPING OF ULTRASOUND ATTENUATION

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Abstract

Defects are characterised by a deviation of the local stress/strain diagram from the one of the material around it, thereby causing enhanced losses where mechanical energy is converted into heat. As the efficiency of this process increases with frequency, the local attenuation of ultrasound (injected e.g. by attached piezoceramic transducers) is a sensitive tool allowing for defect-selective imaging based on detection of local heat generated in an elastic wave field. The sensitivity can be enhanced by using a sinusoidal modulation of the ultrasound. The generated local temperature modulation of the defect area is detected either via the modulated thermal infrared emission (dynamic thermographic imaging) or by the modulated thermal expansion resulting in a pulsating bump on top of the hidden subsurface defect (speckle pattern interferometry). Examples will be presented showing how ultrasound thermography (or sonic thermography) and ultrasound speckle techniques (or sonic interferometry) perform in mapping various kinds of defects.

Introduction

The reliability of defect detection can be highly improved if for inspection a mechanism is involved where a defect responds selectively so that the image contains only the defect and not the confusing background of intact features. This enhances the probability of defect detection and allows for automation of the inspection process. By using elastic waves for sample excitation this aim can be achieved.
Elastic waves launched into the component propagate inside the sample until they are converted into heat [1,2]. A defect causes locally enhanced losses and consequently selective heating while intact areas of the material retain their temperature. Modulation of the elastic wave amplitude results in periodical heat generation so that the defects are pulsating at the modulation (lock-in) frequency [3].
With thermographic mapping of attenuation (Ultrasound Burst Phase thermography – UBPT) the thermal emission of defects is detected with an infrared camera due to the temperature modulation on the surface. It is analysed with the lockin technique tuned to the frequency of amplitude modulation of the elastic waves (Fourier transformation) in order to obtain an image of amplitude and phase of temperature modulation [4-7].
With interferometric mapping of attenuation (Electronic Speckle Pattern Interferometry - ESPI) the thermal expansion due to heat generation at defects is used for imaging [8,9]. The heating results in a local bump on top of the subsurface defect which can be detected by interferometric methods. As the elastic waves for excitation were amplitude modulated, the bump on the surface is pulsating at the modulation frequency. This allows for lockin evaluation of the obtained ESPI images [10].
In this paper results of these two different methods which base on different physical mechanisms are compared. Simultaneous measurements with the same boundary conditions and the same excitation were performed in order to compare the two methods on different kinds of defects and materials.

Methods

In ultrasound activated lockin thermography and ultrasound activated ESPI, an ultrasonic transducer is attached to the surface of the sample from where the acoustic waves propagate into the whole volume. They are reflected inside the sample until they disappear preferably in a defect and generate heat. The high frequencies of the ultrasound (20 kHz) are very efficient for heating since many hysteresis cycles are performed per second. The amplitude of the high frequency output signal is modulated at the low lockin frequency (below 1 Hz) which turns a defect into a thermal wave transmitter. Maximal electrical input power of the used ultrasound transducer is up to 2 kW. Another kind of excitation is the use of short ultrasonic pulses instead of amplitude modulation [1,11].

Thermographic mapping of attenuation (UBPT)

Ultrasound Burst Phase Thermography (UBPT) uses short ultrasound or sonic pulses to excite the sample. The spectral components of the cooling down period after burst excitation provides information similar to the lockin method (amplitude and phase) but much faster [12-14]. A CEDIP Jade II infrared focal plane array camera was used to capture temperature sequences with a frame rate up to 110 Hz. Its InSb 320 x 240 detector array is sensitive in the 3-5 µm regime (figure 1).

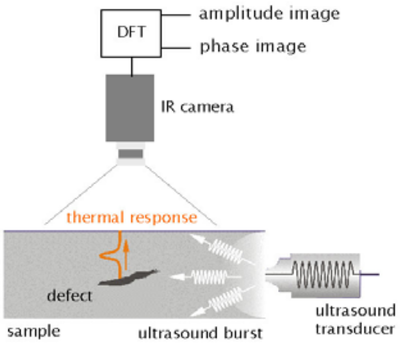


Figure 1: Set up of ultrasound burst phase thermography (UBPT)

Interferometric mapping of attenuation (UBPI)
Electronic Speckle Pattern Interferometry (ESPI) and related methods (e.g. shearography) display changes of surface deformation [15]. In the presented measurements using Ultrasound Burst Phase Interferometry (UBPI) an arrangement for out-of-plane displacement detection with ESPI was used (figure 2). A diffuse reflecting sample is exposed to a laser beam (wavelength 660nm). The image of the object and a reference beam are superposed thereby causing an interference pattern so that the image of the object obtains a grainy structure ("speckle-pattern"). This grainy image is recorded by a CMOS-camera. The superposition of two speckle patterns related to their two deformation states of the inspected object results in a superposed fringe pattern that displays lines of equal deformation of the surface (similar to the equal-height-lines on a map). The distance between two fringes corresponds to a deformation change of half the laser wavelength. Application of phase shifting and fringe unwrapping techniques improve the contrast of the fringes and convert them into absolute displacement values [15,16].
The sequence of images was recorded after the ultrasound burst injection. At each pixel the time dependence of hight change was Fourier-transformed and provided a phase angle image at various frequencies. The ultrasound burst phase ESPI images and their thermographic counterparts shown in this paper were taken at the Fourier component at 0.01 Hz.

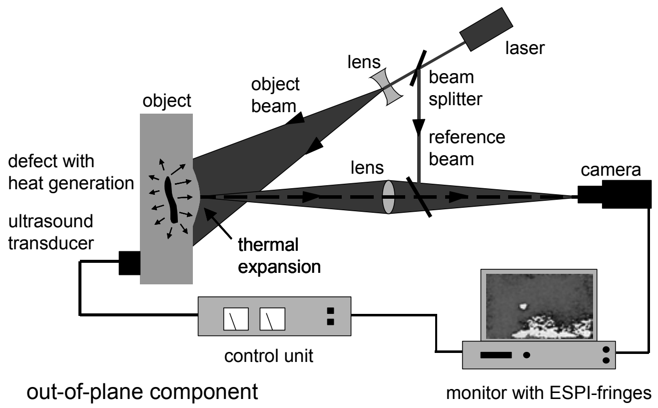


Figure 2: Optical set-up for UBPI with out-of-plane component

Results

Model sample with heating wires
In order to simulate heating inside of the sample, like in ultrasound activated mapping of attenuation, an epoxy resin sample was produced containing embedded heating wires in different depths (figure 3). With this sample it is possible to investigate the correlations of depth range, lateral resolution, and heating power.

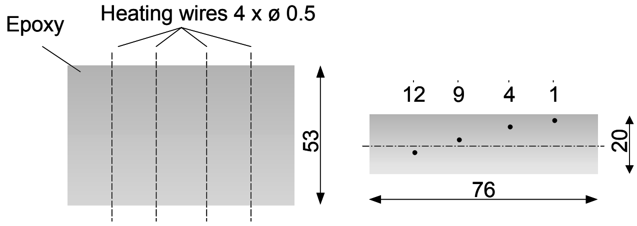
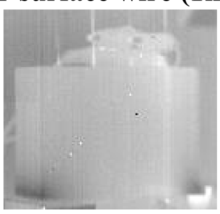
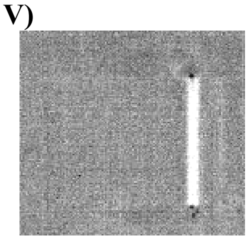


Figure 3: Set-up of model sample with heating wires

Resolution of the heating source (defect) decreases with depth because of heat diffusion and material characteristics involved in ESPI (i.e. thermal expansion). This effect can be observed in the model sample as the voltage for heating of the deeper wires has to be increased (figure 4).

near surface wire (1mm, 0.6 V)

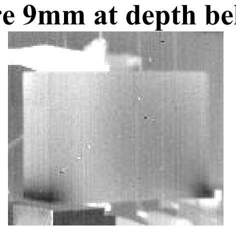

UBPT amplitude image

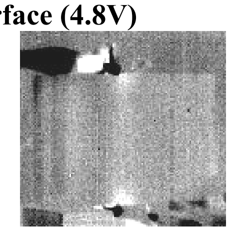

UBPT phase image

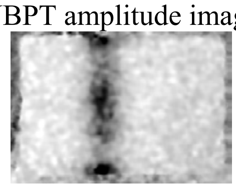

UBPI amplitude image


UBPI phase image

wire 9mm at depth below surface (4.8V)


UBPT amplitude image


UBPT phase image


UBPI amplitude image

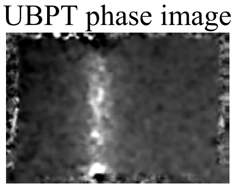

UBPI phase image

Figure 4: Amplitude and phase images of model sample with modulated heating of wire

Though the frame rate of thermography is higher than the video frequency of the ESPI-camera, the ESPI image is obtained much faster due the physical process involved in imaging: Instead of the slow heat diffusion from the heated wire to the surface the information about the thermally expanding area propagates as a deformation, therefore at the speed of sound.
This difference in mechanisms is also the reason why depth range with ESPI is higher than with thermography (figure 4, bottom): The elastic wave is not only faster, but also less attenuated than the thermal wave. These differences in the involved mechanisms also cause a limitation of the ESPI method: Defects which are closer to the rear side of the sample than to the front side are not detectable with ESPI since the induced stress is easier relieved by the closer rear surface.

Model sample with bonding defect
Another model sample simulates bonding defects (figure 5). Injection of elastic waves into the sample heats mostly the bonded boundary while there is no adhesion and no heating where the holes are (that simulate bonding defects).

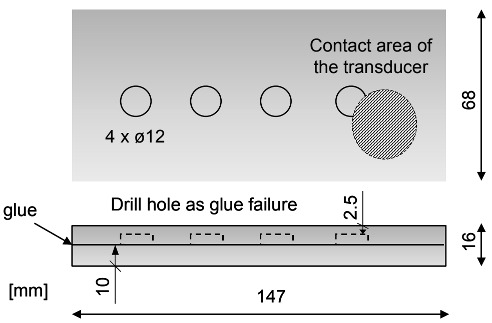


Figure 5: Set-up of model sample with glue failure

The duration of the excitation burst was 100 ms like in the model sample above. Electrical power on the ultrasound transducer was 320 W which is clearly higher than the electrical power applied on the wire sample. Only a fraction of this electrical power is used for heating up the adhesive bond. Most of the power is lost at the coupling of the transducer to the sample.

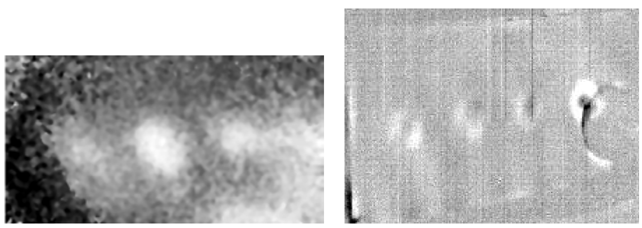


Figure 6: UBP Phase Results on model sample with glue failure UBPI (left), UBPT (right)

The resolution of the holes is better with thermography than with ESPI (figure 6). Investigations to improve our understanding of this difference are in progress.

CFRP sample with heat damage
Near - surface defects were generated on a CFRP plate (295x295x9mm³) by local thermal overload. This produces a degradation of the matrix and causes a local delamination.

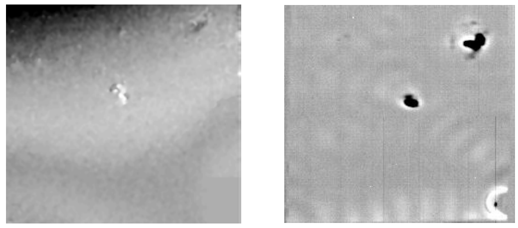


Figure 7: Results on CFRP sample with heat damage. UBPI (left), UBPT (right)

The images of figure 7 show the same defects at both methods. Also a standing wave pattern on the surface of the thermography image is visible. These standing waves occur at simple sample geometries (figure 7, right). Thermography is only seemingly more sensitive to standing wave patterns than UBPI which starts image acquisition immediately after excitation because the excitation amplitudes are too high for the sensitive ESPI system.

CFRP sample with impact damage
A 15mm thick CFRP sample (150x100x15mm³, kindly provided by Prof. Darryl Almond, University of Bath/UK) was impacted. Afterwards it was inspected by thermography (UBPT) and ESPI (UBPI) both on front and rear surface (figure 8).

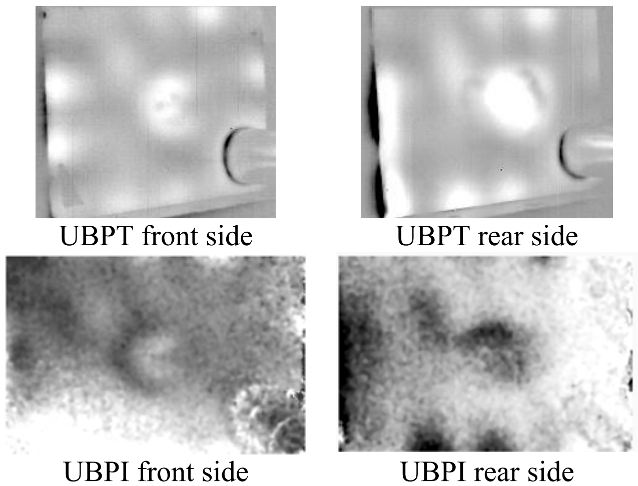


Figure 8: Results on CFRP sample with impact damage. Front side (left), rear side (right)

The results of both methods show an identical standing wave pattern which makes defect detection difficult if no modulation of the ultrasound frequency sweep is applied [17].

Defect size on the rear side appears to be bigger than on the front side which is due to the cone structure of impact damages. This size difference is visible in both the thermography and interferometry image.

Conclusions

In imaging of near-surface damage the lateral resolution of defects seems to be better with UBPT than with UBPI. The reason is the difference in physical mechanisms involved in image generation.

UBPT-images of defects deeper inside the sample seem to be blurred due to heat diffusion or highly attenuated thermal waves which is the alternative description. This attenuation may even prevent the detection of such defects. Here UBPI has a better resolution and a higher depth range. Another advantage of UBPI is the short measurement duration as the bump on the surface caused by the heating up of the damage inside appears at about the speed of sound.

Both methods (with contacting excitation and remote detection) complement each other well, although UBPI as an interferometric method is more convenient for reference measurements in the lab, while the thermography system is much more robust and mobile for applications in industrial environment.

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