

Characterization of Layer–Delaminations by Ultrasonic Speckles

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Abstract. Combined electrical mechanical and thermal loads influence highly structured specimen over time and might cause a variety of failure modes. Some of these failures can be such as to only gradually diminish the nominal behaviour of the components so one cannot conclude there is no evolving problem if nominal function is observed. Standard non-destructive testing methods are only partly able to detect the developing delamination or progressive generation of voids due to stress. These delaminations can cause voids and cracks in the still operative specimen that might never be of any problem in the nominal operating performance but on the other hand they might further the degradation of the component to ultimately result in a catastrophic failure. We investigate the gradual emergence of so-called ultrasonic (US) speckles as a hint to degradation processes deep in the volume of the specimen caused by scatterers (small voids or small cracks) that are too small to be directly imaged by ultrasound techniques. However, due to their density evolving over time they expose themselves by forming US-speckles that increase in contrast over time. In this paper we are applying the well-known theory on optical laser speckles caused by micro roughness on a specimens surface to the formation of ultrasound speckles caused by randomly distributed sub-wavelength scatterers within the volume of a specimen. Both effects are due to random phase variations in the former case operating on laser light caused by height variations of the scattering profile and in the latter case by sound velocity variations along the propagation path within a specimens volume. We can show that the speckle contrast is a good measure of the average total volume of scattering voids and thus of the onset and evolution of delaminations as defined by Goodman of partly developed speckles.

keywords: ultrasound speckles, non-destructive testing, layer delamination, randomly distributed scatterers

1. Introduction

There are a variety of non-destructive testing schemes allowing to tomographically scan a specimen for voids or cracks deep in the volume — going from fine to coarse resolution — like X-ray diffraction [1], acoustic near-field techniques (SNAM) [2], micro computed tomography scans, scanning acoustic microscopy [3, 4] and thermography techniques [1]. All mentioned techniques are essentially aiming for the detection of each and every (developing) void and thus require an appropriate spatial resolution and significant scanning and processing time. In our contribution we are not aiming for the detection of single failures but are modeling the degradation as randomly scattered acoustic phase objects representing a volume density of voids that is tomographically analyzed using an acoustic microscope. In the acoustic scanning microscopy technique [5] these sub-resolution random scatterers are causing ultrasound speckles



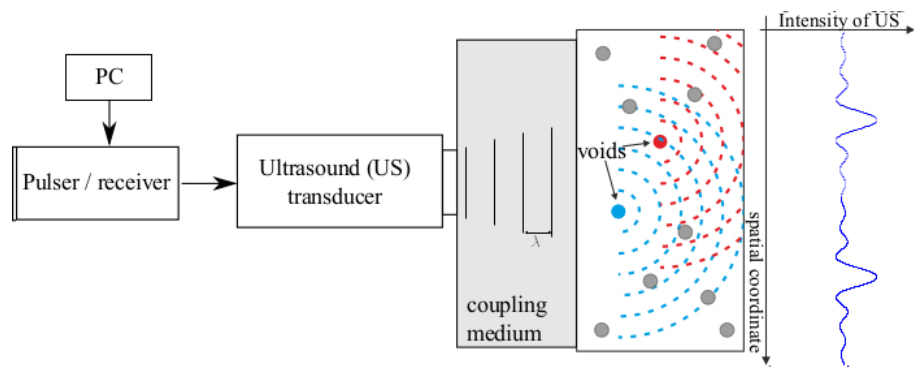


Figure 1. Experimental setup. Voids in the specimen cause diffraction effects. The superposition of resulting waves cause speckles in the acoustic microscope image of Fig. 3.

[6]. These speckles are developing over stress cycles with respect to the initial state of the homogeneous specimen beginning with zero phase deviations over partly developed speckles for specimen in the void initiation phase to fully developed speckles [7] for specimen experiencing sufficiently many randomly scattered voids [8, 9].

Coherent imaging systems be it synthetic aperture radar imaging, laser scanner based imaging systems [10, 11, 12] or be it ultrasonic imaging experience the presence of speckle noise overlaid onto the range image, the laser scan image or the echogenicity map in ultrasound images. Speckles themselves are a random but still deterministic interference pattern in an image that most of the time has a negative impact on the measurement problem at hand. Speckles, however, convey sufficient information for some other measurement problems since e.g. in laser applications they act like fingerprints of an analyzed surface element whose motion can thus be tracked with sufficient resolution [13].

In ultrasonic imaging speckles are typically reducing the ability to detect fine structures in a specimen by masking its echogenicity. They are formed with coherent radiation of a specimen presumably containing many sub-resolution scatterers [14].

In some fields the development over time of the density and average size of voids can be an indicator to the overall thermal or mechanical stress the specimen was to bear. Most of the time the specimens are keeping their nominal operating performance even if they exhibit a moderate density of cracks and voids with sizes below the detection limit of acoustic microscopes. The idea conveyed in this paper is to utilize the temporal development of speckle noise overlaid onto the B-mode scan of a specimens structure to estimate the average density and possibly size of sub-resolution scatterers (voids or cracks). It is organized as follows: in Section 2 the experimental set-up is described. Section 3 details the theory of speckle noise in US images and derives the speckle contrast as a measure of void density. Section 4 presents first results of an acoustic microscope adapted to the detection of voids and cracks. The outlook concludes the paper.

2. Experimental set-up

Our experimental set-up consists of a Panametrics NDT Mod. 5900 PR pulser receiver, driving a Panametrics 20 MHz transducer V390 with a 0.25 inch element size and a 0.5 inch focal length. An Agilent Infiniium DSO 9254A oscilloscope is used to digitize the US-return with a preset sample rate of 1 Gsample/s (depth resolution approximately $1.5\mu\text{m}$ for the typical material of the specimen). The mechanical scanner is a Linos x-act LT 100-1 three-dimensional translation stage (resolution $1\mu\text{m}$). All the processing is done in Matlab as is the visualization. Volume data is rendered using ParaView open source software. Figure 1 shows our set-up schematically.

Figure 2 shows the temporal impulse response of the transducer with a relative bandwidth of

70% of center frequency in the left panel and the spatial impulse response — the so-called point spread function — schematically in the right panel.

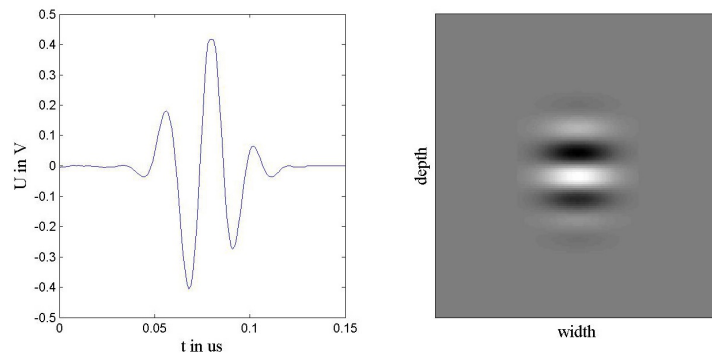


Figure 2. Left diagram: temporal impulse response of a Panametrics 20 MHz US transducer. Right panel: spatial impulse response (point spread function) of the same transducer in the focal plane.

3. Theory of US-speckles

This section is modelling the statistics of US-speckles based upon some simplifying assumptions. (A) that the carrier frequency ν (in our case 20 MHz) is sufficiently monochromatic to exhibit a coherence time that allows the constructive or destructive interference of contributions from scatterers located in the resolution cell of the set-up. For our case this can be interpreted in the temporal domain to have a pulse length of approximately $0.1\mu\text{s}$ as can be seen from Fig. 2 left panel equating to approximately $120\mu\text{m}$ in depth dimension. (B) in the spatial domain the transducer focuses to approximately $10\mu\text{m}$ (FWHM) as is schematically depicted in Fig. 2 right panel. (C) Thus the resolution cell is cigar-shaped with said dimensions.

The sound pressure is modeled as a complex phasor

$$\underbrace{u(x, y, z, t)}_{\text{temporal \& spatial}} = \underbrace{A(x, y, z)}_{\text{spatial}} \cdot \underbrace{e^{j2\pi\nu t}}_{\text{temp.}}$$

with u representing spatial and temporal variations, A , the complex phasor magnitude, and ν the center frequency. The complex phasor A can be decomposed into its magnitude $|A|$ and phase term $e^{j\Theta(x,y,z)}$.

The complex phasor A results from the summation over all (index n) contributions of single scatterers in the resolution cell with the following assumptions: (A) amplitude a_n and phase Θ_n of the n th scatterer are statistically independent of each other and of all other scatterers in the resolution cell. (B) the phases of the scatterers are uniformly distributed in $[0, 2\pi)$, which means that their spatial distribution is such as to allow many wavelength λ in between them either in depth or lateral direction. Now further applying the central limit theorem allows to express A as the coherent sum of scaled contributions a_n , where the scale factor $\sqrt{N}$ takes into account the decreasing magnitude of single contributions if their number N increases.

$$A(x, y, z) = \frac{1}{\sqrt{N}} \sum_{n=1}^N |a_n| \cdot e^{\Theta_n}$$

Analyzing the probability density function for A one can show [11], that a circular Gaussian PDF results.

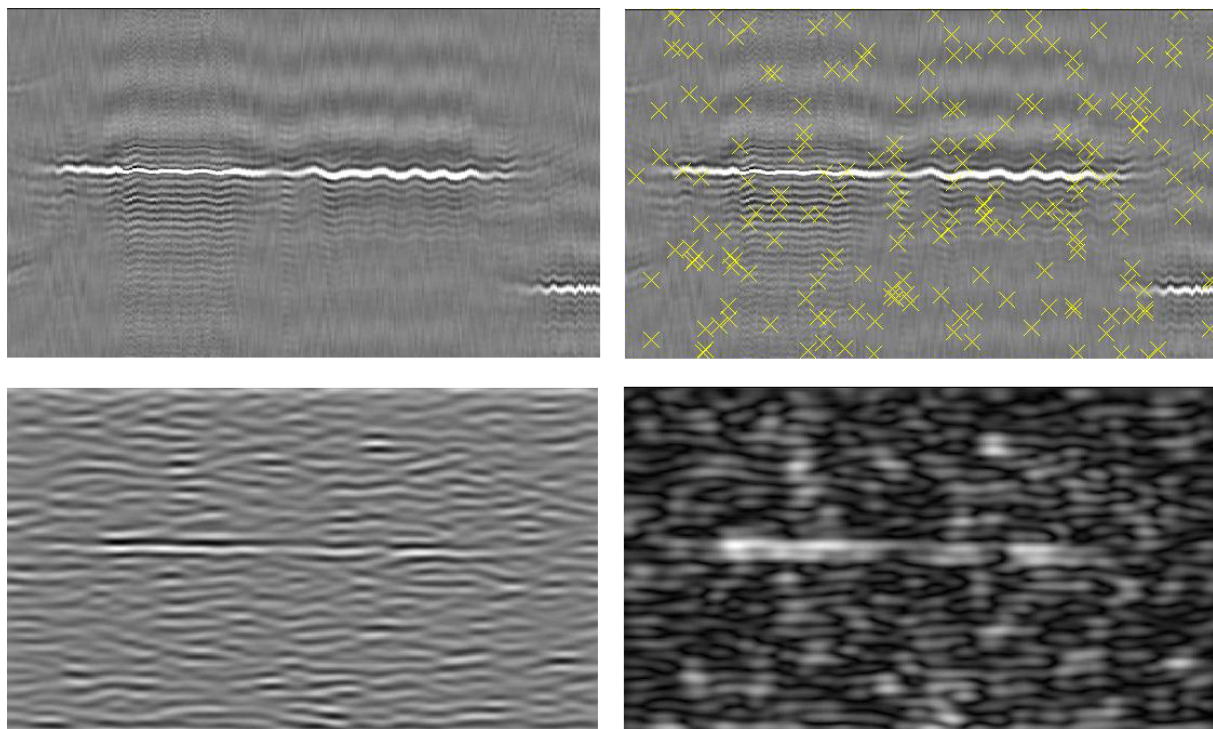


Figure 3. Ultrasound image of the cross-section of a specimen with some pronounced structure top left (remark: the waviness of the imaged structure very likely is caused by the non-ideal mechanical guide of the 3D translation stage.); Top right: the same global structure with corresponding scattering function. This scattering function is derived from a randomly distributed population of sub-resolution scatterers (yellow $\times$'s). The scattering function is spatially convolved with the point spread function of the ultrasonic transducer (bottom left); Envelope demodulation of the RF-carrier (here a 20 MHz center frequency, 70% relative bandwidth transducer) exhibiting strong speckles bottom right.

Going a step further and assuming that in addition to the random weakly scattering scatterers there is a deterministic structure present that would add a rather strong coherent contribution to A , it can be shown (again [8, 11]) that a Riccian PDF will result.

$$p_A(a) = \frac{a}{\sigma^2} \cdot e^{\left(-\frac{a^2+s^2}{2\sigma^2}\right)} \cdot I_0\left(\frac{as}{\sigma^2}\right) ; \quad a \geq 0 \quad (1)$$

Here I_0 is the Bessel function of the first kind with order zero, σ is the standard deviation of the circular Gaussian PDF alone, and s is the strong coherent scattering of the deterministic structure. In analyzing Eqn. 1 one can conclude that the image contrast as defined by the variation of intensity in a flat region of the image in relation to the mean brightness (caused by the deterministic structure) is a statistical parameter measuring the impact of density and average size of the sub-resolution scatterers sought.

4. Measurement results

In order to demonstrate the applicability of the method one would have to resort to the acquisition of a rather lengthy experimental procedure where the specimen needs to be stressed for many thousands of loading cycles without being spatially displaced within an acoustic microscope. The necessary experimental equipment is currently under development and is thus not available

yet to acquire real data. For that reason we did in fact acquire true US volume data which was appropriately demodulated using the Hilbert transform method to show in 3D the internal structure of the specimen. Subsequently randomly distributed scatterers of various echogenicity were added and the volume data again convolved with the point spread function shown in Fig. 2 to exhibit US speckles. This process is described in more detail next. Speckle are present both in the RF data and the envelope – detect data as is shown in Fig. 3 for example. The top left panel shows the echogenicity map without random sub-resolution scatterers. The top right panel shows the scattering function by adding artificially some hundred sub-resolution scatterers. The bottom left panel shows the simulated ultrasound RF data obtained from scanning spatially the echogenicity. The simulation is done by convolving in lateral dimension and in the time (depth) dimension with the assumed point spread function of the transducer as depicted in Fig. 2.

The bottom right image is formed by demodulating the RF data to yield the complex envelope whose magnitude is then imaged in grayscale resulting in this very obvious noisy (speckled) image of the original echogenicity (top left).

These speckled data set was then statistically analyzed giving the result shown in Fig. 4. One can clearly observe the increase in the variance σ_I^2 of the image intensity within the presumed flat area boxed, which is a measure of speckle contrast.

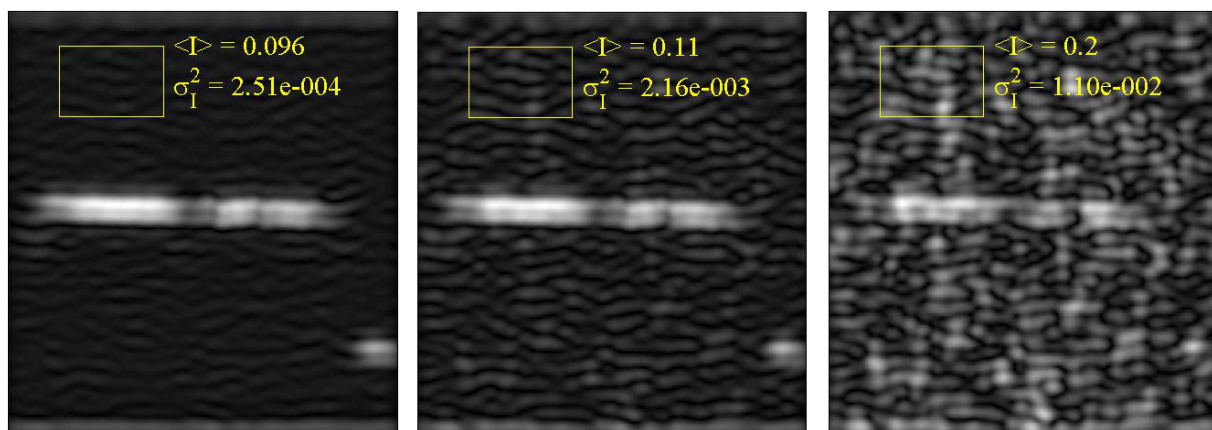


Figure 4. Three B-mode scans exhibiting US speckles in increasing magnitude. All frames were generated adding 5000 sub-resolution scatterers (size $\approx \lambda/50$) each with relative scattering strength of -60 dB, -54 dB and -40 dB relative to the deterministic component (the bright horizontal bar) going from left to right. One can clearly observe the increase in the variance of the intensity σ_I^2 .

In Fig. 5 the complete data set is 3D rendered to show the internal structure of the specimen.

5. Conclusions

We have demonstrated that US speckles typically considered a nuisance to be avoided in ultrasonic imaging can be exploited nicely to indicate the emergence of sub-resolution scatterers which might be caused by micro-cracks or small sized delaminations still small enough not to impair the nominal functionality of the specimen but possibly being indicative of an upcoming failure.

Acknowledgments

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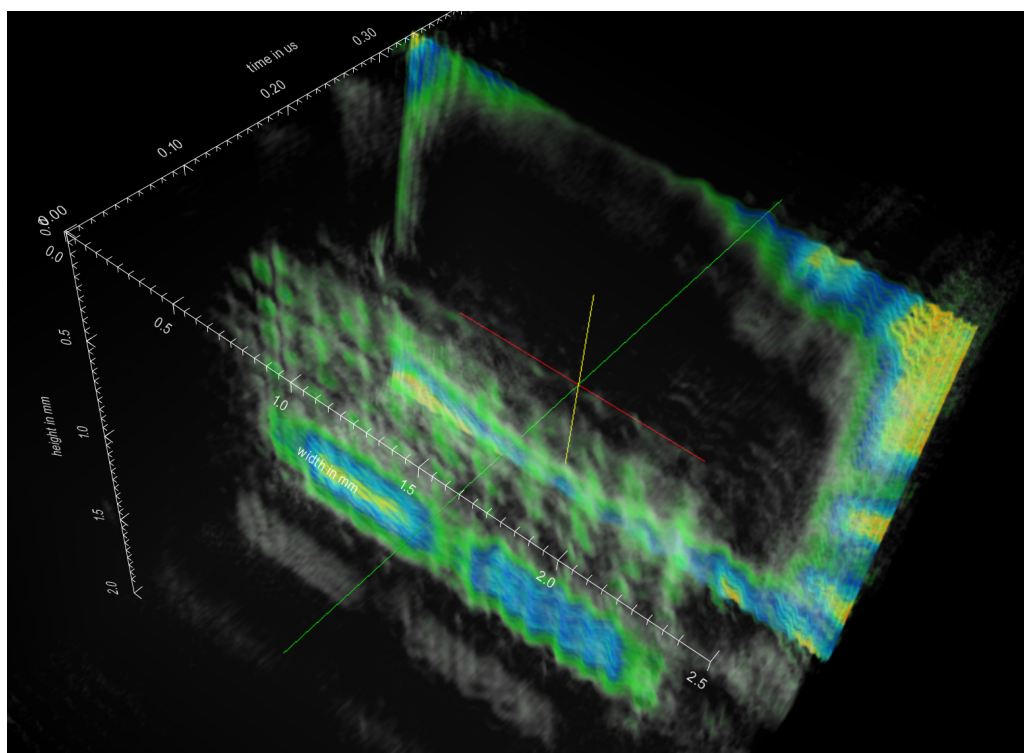


Figure 5. Ultrasound volume data rendered using the ParaView software [15].

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