Thermal wave imaging using lockin-interferometric methods

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Abstract. We report about a technique where we transferred the Lockin-principle from
Lockin-thermography to interferometry to perform thermal wave lockin-interferometry. This
technique is based on speckle-interferometric imaging of periodical height changes going along
with the temperature modulation in a thermal wave. We used both electronic speckle pattern
interferometry and shearography setups and operated them with low frequency periodical heat
deposition while a stack of interferometric fringe patterns was recorded. After unwrapping,
each pixel of the stack was Fourier-analysed at the Lockin-frequency, giving an amplitude im-
age and phase image of low frequency thermal deformation. Though this is very much like
Lockin-thermography, the image generating mechanism is substantially different: The thermal
wave generates periodical thermal expansion correlated with an overall deformation where the
depth integral of the thermal wave is involved. At such a low frequency (below 1 Hz), defor-
mation occurs simultaneously everywhere except in areas where thermal wave propagation is
modified e.g. by boundaries, which affect the phase of deformation. Depth range is adjusted
via modulation frequency as in lockin thermography.

1. Introduction
The topic of this conference is thermal waves that can be monitored in substantially different ways all
of which have in common that they are based on some kind of temperature sensitive effect (e.g. infra-
red thermal emission or thermal expansion of the sample or of the medium to which it is attached).
After photoacoustic [1-3] and interferometric detection [4] being used in the early days for thermal
wave imaging, radiometric detection [5] has become more popular especially after it resulted in
lockin-thermography providing phase angle images within a short time [6-9]. Besides optical excita-
tion there are some alternatives resulting in e.g. ultrasound lockin thermography [10] and induction
lockin thermography [11]. As all of them use well-working commercial thermography cameras acting
as multichannel lockin radiometric devices, there has been not much effort to improve interferometric
imaging of thermal waves, especially since the early interferometric technique was a slow point-by-
point raster scan similar to the first lockin radiometric images.

However, considerable progress has been made since then in interferometry [12], so the time has
come to reconsider how well this technique performs if it is combined with the Lockin-principle [13].
This is the background for our paper. We describe how low frequency thermal wave lockin-
interferometry works and what the results obtained on real life samples look like.
2. Measurement technique
Thermal waves are being applied in various fields, one of which with increasing relevance is non-destructive evaluation where it is important that images can be obtained and interpreted rapidly. Electronic speckle pattern interferometry (ESPI) is a technique that displays the deformation of an object between two states of deformation. The deformation is coded by a fringe pattern where each fringe is a line of equal deformation, with a height difference of half a laser wavelength between adjacent fringes. The fringes themselves are generated by superposition of speckle patterns resulting from interference effects between two very similar structures, very much like the Moiré-effect. The deformation can be achieved e.g. by mechanical load, by variation of internal or ambient pressure or by thermal expansion. If the sample is exposed to modulated light like in conventional thermal wave generation, the periodically heated surface causes a periodical bending. At very low frequencies much below mechanical resonances, the whole body deformation has the same phase everywhere unless the periodical heat flow is affected by boundaries. In that case thermal wave interference results in a local delay of deformation. This is the point of interest since the deviation from the otherwise synchronous deformation means that a boundary reveals itself by the phase lag caused by it.

The way how phase is extracted in this lockin-interferometry is similar, though more complicated than in lockin thermography: During the slow periodical deformation, interferometric fringe patterns are recorded continuously which are then converted into a stack of images showing modulated thermal expansion. By application of a Fourier transformation at the modulation frequency, this motion is analysed in terms of amplitude and phase, therefore the information contained in the stack of images is compressed into just two data per pixel thereby giving finally one amplitude image and one phase image. In the latter one the whole body deformation is eliminated this way, thereby increasing the dynamic range. We found that the improvement of signal to noise ratio is up to one order of magnitude.

The speckles in ESPI depend on interference effects between a reference beam and the object beam. As the reference beam does not coincide with the imaging beam, vibrations cause a noise of the speckle pattern. This problem is much reduced if the two beams are very close to each other which is achieved if interference occurs by superposition of two images which are slightly tilted with respect to each other. In that case (“shearography”), the fringe pattern looks much different than before since instead of a local phase bump it indicates the derivative of it along the direction of tilt. As the positive slope appears bright and the negative dark, shearography images display bumps as if they were illuminated from the side.

![Figure 1. Suppression of whole body deformation. One conventional ESPI image from the stack (left) and resulting lockin phase angle image (right) obtained on the same sample provided with rear surface holes.](image-url)
We used the setup in Fig 3 where the lamp generates remote modulated heating and resulting deformation modulation while the laser is used for shearographic imaging of this deformation.

![Figure 3. Setup for Lockin-Shearography.](image)

The sensor is a conventional shearography camera generating two images that are slightly tilted with respect to each other due to a modified Michelson setup. Superposition of the two images results in fringes indicating the derivative of the deformation state.

Phase change as a function of boundary depth (Fig 5) shows that depth range of Lockin speckle-interferometry is by about 50% larger than in Lockin thermography. The reason is that the integral of the thermal wave is involved in signal generation instead of its surface value just like in piezoelectric thermal wave detection investigated more than two decades ago [14].

![Figure 4. Phase angle along aluminum wedge that disappears gradually under an epoxy layer.](image)
3. Examples
An example taken on an about 1m² sized CFRP structure provided with rear surface stringer structure was inspected remotely on the flat outer surface at 0.008Hz with Lockin-Shearography. The area with hidden damage (stringer disbond) is revealed clearly by a locally enhanced phase angle structure.

![Figure 5. Test panel of an aircraft. Stringer areas disbonds in buckling test are afterwards revealed in the phase angle image (see arrow).](image)

While the example above was a test sample (though built like on a real aircraft), the CFRP/foam-sandwich rims shown in Fig. 6 are in-service parts of the Stuttgart University racing car that was built for the “formula student”. These rims’ weight is half the one made from aluminium, but they are more sensitive to damage. Lockin-Shearography measurements revealed cracks in all torque arms.

![Figure 6. CFRP rim on racing car. Middle: intact. Right: damaged rim (cracks, see white marks).](image)

4. Conclusion
Lockin interferometry has the same advantages as lockin thermography in terms of phase angle images and depth profiling capability. However, there are some additional benefits: The detector array is a high-resolution CMOS camera with many more pixels than in IR detector arrays, also they are much cheaper than their thermographic counterparts. Depth range is larger than in Lockin thermography due to the way of signal generation. Of course this technique depends on thermal expansion, so ceramics are not the best to be inspected this way, but it performs well on polymers and composite materials.

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