46th Annual Review of Progress
in Quantitative Nondestructive Evaluation
QNDE2019
July 14-19, 2019, Portland, OR, USA

QNDE2019

PHOTOTHERMAL SUPER RESOLUTION IMAGE RECONSTRUCTION USING STRUCTURED 1D LASER ILLUMINATION

Samim Ahmadi[1], Erik Thiel, Christina Karagianni, Philipp Hirsch, Mathias Ziegler
Bundesanstalt für Materialforschung und -prüfung (BAM)
12200 Berlin, Germany

Peter Burgholzer
RECENDT
Research Center for Non-Destructive Testing,
Linz, Austria

Günther Mayr
Josef Ressel Center for Thermal NDE of Composites,
University of Applied Sciences Upper Austria,
Wels, Austria

Peter Jung, Giuseppe Caire
Technical University of Berlin,
Department of Telecommunication System,
Berlin, Germany

ABSTRACT

The separation of two closely spaced defects in fields of Thermographic NDE is very challenging. The diffusive nature of thermal waves leads to a fundamental limitation in spatial resolution. Therefore, super resolution image reconstruction can be used. A new concerted ansatz based on spatially structured heating and joint sparsity of the signal ensemble allows for an improved reconstruction of closely spaced defects. This new technique has been studied using a 1D laser array with randomly chosen illumination pattern.

This paper presents the results after applying super resolution algorithms, such as the iterative joint sparsity (IJOSP) algorithm, to our processed measurement data. Different data processing techniques before applying the IJOSP algorithm as well as the influence of regularization parameters in the data processing techniques are discussed. Moreover, the degradation of super resolution reconstruction goodness by the choice of experimental parameters such as laser line width or number of measurements is shown.

The application of the super resolution results in a spatial resolution enhancement of approximately a factor of four which leads to a better separation of two closely spaced defects.

Keywords: super resolution, photothermal, image reconstruction, laser array, defect separation

NOMENCLATURE

CS	Compressed Sensing
SR	Super Resolution
IJOSP	Iterative Joint Sparsity
F-SAFT	Frequency Domain Synthetic Aperture Focusing Technique
FWHM	Full Width Half Maximum

1. INTRODUCTION

The use of laser arrays in terms of active thermography enables a spatially and temporally structured heating and opens new fields for research activities [1,2]. One field of application for laser arrays is the super resolution laser thermography which deals with the separation of closely spaced heat sources.

Super resolution (SR) techniques are well-known from optics [3,4]. Inspired from this idea, scientists in fields of nondestructive testing such as photoacoustic [5] or terahertz [6] extended the scope of application. Even in fields of thermography there are first approaches [7], but in this work flash lamps have been used as excitation sources.

To realize SR methods, the theory of compressed sensing (CS) is used, which was introduced in 2005 by Tao et al. [8]. It can be used in non-destructive testing to find the optimal solution for the reconstruction of the defects under investigation. For this purpose, an underdetermined system must be set up which can be solved by processing the measurement data with knowledge of certain system properties.

In this paper we make use of the existing SR approaches such as the IJOSP algorithm. We adapt and apply the SR algorithm to our processed measurement data which is generated by photothermal measurements using 1D laser illumination. The goal is to separate closely spaced defects and therefore to enhance our spatial resolution with spatially and temporally structured heating. Moreover, the influence on the results of the IJOSP algorithm by new data processing techniques, a variation of experimental parameters such as the laser line width or the number of measurements per position should be discussed.

[1] Contact author: samim.ahmadi@bam.de

2. MATERIALS AND METHODS

The nature of heat diffusion in a material limits the separation of closely spaced defects. Figure 1 suggests the resolution problem.

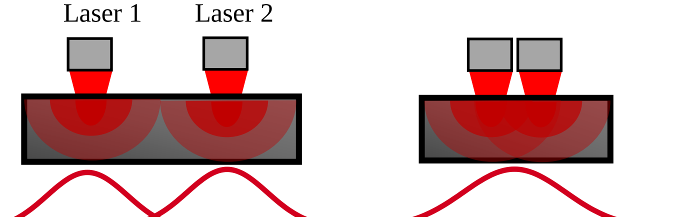

Figure 1: Resolution problem using two heat sources with small distance

If a sample is illuminated from the front with a strongly focused laser beam, heat is generated. The heat is blurring over the depth of the sample. This fact complicates the separation of two closely spaced lasers as heat sources while measuring with the infrared (IR) camera in transmission configuration (see figure 1). The measured temperature over position diagram leads to an assumption of one heat source instead of two heat sources if their distance is too small. Therefore, the questions we need to ask are: (1) How can we resolve two closely spaced heat sources? (2) What influences the resolution capability? (3) How far can we go?

2.1 Experiment

The used experimental setup is shown in figure 2. The laser array is a vertical-cavity surface emitting laser (VCSEL) array and offers an optical output power of 2.4 kW in an area of 52 x 40 mm at a wavelength of about 980 nm. The VCSEL array cells are controlled by National Instruments myRIO controller, which is equipped with a FPGA and thus allows real-time control. The IR camera (Infratec Image IR 9300) was used in full frame (1280 x 512 pixels) with a spatial resolution of 70 µm per pixel. The collimation and focus lenses have the same focal length so that the distance between the light source and the collimating lens as well as the distance between the focus lens and the specimen determine the optical magnification factor in terms of imaging. In this experiment an optical magnification factor of ¼ was used.

In this setup, a so-called "blind structured illumination" is used to create the optimal conditions for the application of the IJOSP routine. Blind illumination means that no prior information about the illumination pattern (i.e. the spatial heat source distribution) is used for reconstruction. The IJOSP algorithm works well if the optical excitation is chosen randomly in space [9]. Furthermore, the SR routine is optimized in its reconstruction goodness if we are able to find a sparse matrix representation of the data. This property is given by two features. Firstly, in the experiment shown in figure 2 only the slit regions are heated up and lead to a significant heating. Secondly, a sparse basis is found via the Virtual Wave (VW) concept that will be

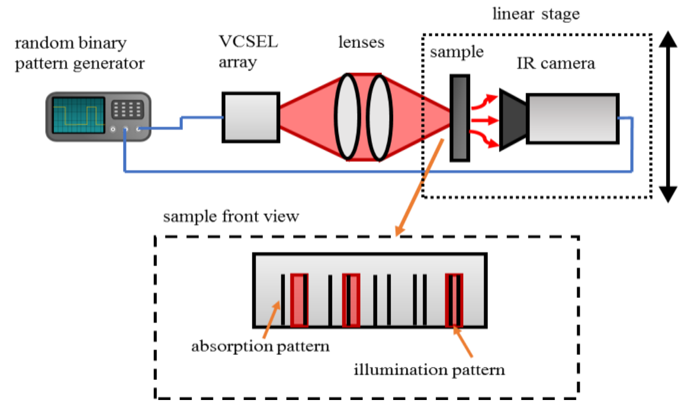

Figure 2: Experimental setup for generating thermographic data that is suitable for super resolution image reconstruction in transmission configuration. The binary pattern generator controls the VCSEL array cells randomly so that blind structured laser illumination is realized. Using a linear stage enables to shine on different spots on the sample surface. The sample is a 3 mm thick blackened steel sheet where aluminum foil is glued on the sample front surface. The sample front view shows an example of an illumination pattern since the VCSEL array has 12 laser lines (cells) that are controlled randomly. In this case 3 of the 12 VCSEL array cells are turned on (illumination pattern). An absorption pattern was applied to the sample surface by cutting slits into the aluminum foil. This leads to increased heating in the slit region. The absorption pattern contains 5 slit pairs with varying distances (3.0, 2.0, 1.3, 0.9, 0.6 mm). The goal is to resolve even the slit pair with the smallest distance using the IR camera in transmission configuration. For this reason, multiple measurements at different positions are done.

discussed in the next section. Finally, according to multiple measurement vector (MMV) theory [10], the SR routine requires multiple measurements with different illumination patterns at different positions so that each slit in the aluminum foil is hit by the laser cells. The measurement data was generated by doing ten measurements per position. The ten measurements differ due to the randomly chosen illumination pattern. Measuring at 15 positions results in 150 measurements that are used then in data processing.

2.2 Data processing

The measured temperature matrix of the IR camera in transmission configuration at $z = L$ is designated as $T^i_{meas}(x, y, t)$, whereby i stands for the number of measurement and L for the thickness of the specimen. Since we are dealing with vertically oriented slits, the lateral heat flow in x-direction is of interest. For this reason, the mean is taken over the height (y-direction) so that we focus on $T^i_{meas}(x, t)$. The following steps are inspired by the data processing method of Burgholzer et al. [7].

The application of the Virtual Wave (VW) concept [11,12] enables to transform the measured thermal waves to virtual ultrasound waves $T^i_{virt}(x, t)$. Using an ultrasound reconstruction algorithm such as Frequency Domain Synthetic Aperture Focusing Technique (F-SAFT) enables to create a sparse basis representation of the measurements that includes an elimination of the time dimension so that a first reconstruction $T^i_{rec,FSAFT}(x)$ is obtained. This matrix is then used as input for the IJOSP routine that has already been well described [7]. The use of the IJOSP routine results in a matrix that is designated as $T^i_{rec,IJOSP}(x)$ and taking the sum over *i* results in $T_{rec,IJOSP}(x)$.

3. RESULTS AND DISCUSSION

To emphasize the effect of using the previously described data processing steps, the diagram in figure 3 compares the mean over i of $T^i_{meas}(x, t = t_m)$ (red curve) and $T_{rec,IJOSP}(x)$ (blue curve) whereby t_m stands for the time at which the IR camera measures the maximum temperature of the whole sequence.

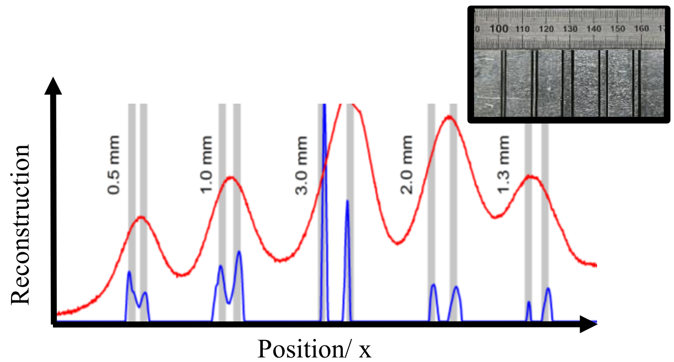

Figure 3: Reconstruction results using VW + F-SAFT + IJOSP algorithm (blue) vs mean over pixels in height of thermographic raw data (red). Upper right corner: Image of the sample front surface

Figure 3 shows that each slit can be resolved. Comparing the full width half maximum (FWHM) of a red curve peak with the FWHM of a blue curve peak indicates the spatial resolution improvement. Calculating the ratio of both FHWM values results in a spatial resolution enhancement of a factor of approximately four.

As described in the experimental part of this paper, the image dimensions have been reduced by using a suitable lens configuration. This laser line width reduction leads to a higher reconstruction quality since the width of the heat source on the sample surface depends on the width of the chosen laser lines. The same effect could be investigated by increasing the excitation pulse length. Both parameters lead to an effective broadening of the thermal foot print on the front side. This effect can be modeled by a convolution with the Greens function (i.e., the thermal point spread function).

However, it should be considered that the measurement duration increases with smaller illumination patterns, because more measurements are needed to cover the entire sample surface, which means that it exists a trade-off in choosing the optimal experimental parameters.

4. CONCLUSION

This work has shown that the use of SR algorithms such as IJOSP results in a spatial resolution enhancement also in the field of laser thermography. But it should be considered that the experimental parameters and the whole measurement procedure meet the conditions for using SR algorithms.

This is a big step towards precise defect detection in laser thermography and overcomes the limitations known from conventional thermographic reconstruction.

Since this work concerns to a 1D reconstruction, the future work refers to 2D and 3D reconstruction as well as measurements in reflection configuration. Moreover, new SR algorithms besides IJOSP will be investigated to evaluate the potential of photothermal SR imaging.

REFERENCES

[1] Thiel, Erik. *Int J Thermophys*, **40** (2), 2018
[2] Ziegler, Mathias. *Materials Testing*, **60** (7-8), 2018
[3] Klar, T. A. *Opt. Lett.*, **24** (954), 1999
[4] Hell, S. W. *Opt. Lett.*, **19** (780), 1994
[5] Haltmeier, Markus. *J. Opt.*, **18** (11) 2016
[6] Augustin, Sven. *J of IR, mm, THz waves*, **36** (17), 2015
[7] Burgholzer, Peter. *Apl. Phys. Lett.*, **111** (031908), 2017
[8] Tao, Terence. *IEEE Inf Theory*, **52** (12), 2006
[9] Cai, T. Tony. *Ann. Statist.*, **39** (3), 2011
[10] Mishali, Moshe. *IEEE Sign Proc*, **57** (3), 2009
[11] Burgholzer, Peter. *J of Apl. Phys.*, **121** (105102), 2017
[12] Mayr, Günther. *NDT & E Intern.*, **100**, 2018

