DOI 10.5162/SMSI2020/C4.1

New techniques in super resolution photothermal imaging for nondestructive testing

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Summary:
In this work we focus on our most recent studies to super resolution (SR) laser thermography. The goal of SR nondestructive testing methods is to facilitate the separation of closely spaced defects. We explain how to combine laser scanning with SR techniques. It can be shown that stepwise as well as continuous scanning techniques are applicable. Finally, we discuss the effect of several experimental parameters and image processing techniques to find the optimal SR technique which leads to the highest reconstruction quality within laser thermography.

Keywords: super resolution, laser thermography, nondestructive testing, laser scanning, photothermal imaging

Introduction

The diffuse nature of heat is mainly responsible for not being able to resolve two closely spaced defects with an infrared (IR) camera. The IR camera measures a Gaussian shaped temperature rise over both defects.

SR techniques have already been used in other scientific areas and are well-known such as in optics [1]. Even in nondestructive testing, SR techniques have been applied, for example in photoacoustics [2]. SR can be realized differently, but all these SR techniques have the same goal which is to enhance (artificially) the spatial resolution to improve the details in the image.

In the recent past, photothermal super resolution techniques have shown that it is possible to overcome the conventional resolution limits in thermography. We could obtain more information in our thermal images by performing appropriated experiments as well as applying image processing algorithms to the measured data.[3].

Since laser scanning is easy to combine with thermography and therefore of high interest for industry in terms of nondestructive and contactless testing [4], we made studies on the applicability of SR techniques. We investigated the influence of experimental parameters such as the laser line width or laser pulse length on the reconstruction quality. We also analyzed the effect of image processing techniques such as superimposing different measurements or choosing suitable regularization parameters for optimizing our reconstruction results e.g. using compressed sensing based algorithms like the iterative joint sparsity (IJOSP) approach [5].

Methods

To understand how super resolution techniques can be applied in laser line scanning thermography, it is advisable to describe the measured temperature data from the IR camera mathematically. For reflection configuration (we are measuring with the IR camera from the same side where we illuminate at) our temperature field can be described as follows [6]:

$$T(x, z=0, t) = T_0 + \frac{2}{\rho c_p \pi 4\alpha} \cdot$$
$$\int_0^t \int_{-\infty}^{\infty} q(x-\tilde{x}, t-\tilde{t}) e^{-\frac{(x-\tilde{x})^2}{4\alpha(t-\tilde{t})}} \frac{d\tilde{t}}{\tilde{t}} \, d\tilde{x} \,, \quad (1)$$

where T_0 stands for the initial temperature, ρ for the mass density, c_p for the specific heat, α for the thermal diffusivity, q for the heat flux density. The variation of the laser pulse length is considered by the convolution in time with the variable $\tilde{t}$ and the variation of the laser line width is considered by the convolution in space with the variable $\tilde{x}$.

Within our SR studies [3, 7] we rewrite equation (1) by using the following equation which describes temperature differences:

$$\Delta T(x, z=0, t) = T(x, z=L, t) - T_0 = A \cdot x, \quad (2)$$

whereby A represents the thermal point spread function (PSF) which can be described as a Green's Function as a solution of the underlying heat diffusion equation considering the laser line width and laser pulse length. x simply stands for the defect structure in our investigated material, hence x represents absorption coefficients in space.

Since x is - as it describes our defects in space - the variable of interest, we can determine x by calculating the inverse of A according to equation (2). Unfortunately, it is an ill-posed problem so that optimizers have to be used which are looking for a solution for x which leads to $\Delta T - A \cdot x \rightarrow 0$. In our post-processing algorithms we made use of the knowledge of A.

Results

Figure 1 (b) shows an exemplary result after applying the so-called Block-Elastic-Net optimization to the measured data shown in Figure 1 (a).

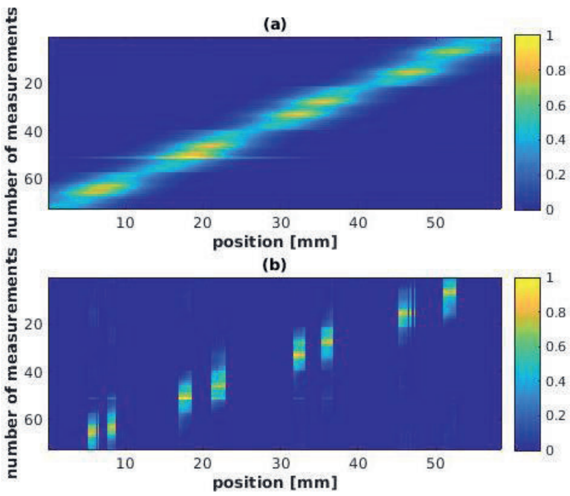

Fig. 1. (a) Measured temperature difference data normalized by the maximum temperature value is shown. We measured films with the infrared camera for each position with a position shift of 0.2 mm. To create this diagram we took the maximum thermogram and calculated the mean over the vertically arranged pixels of the maximum thermogram. One measurement number refers to a measurement at one position. (b) Making use of the Green's function that describes the heat propagation and considering the pulse length of the laser within our used optimization routine Block-Elastic-Net, we found a solution for x which is illustrated in this diagram. The resulting amplitude values are again normalized by the maximum amplitude.

In our studies we have investigated different scenarios by varying experimental parameters such as the laser pulse length and the laser line width. It turned out that it is beneficial to use narrow laser lines as well as short pulses due to the fact that the thermal PSF does not get wider which makes sense from a super resolution point of view.

Furthermore, we discovered post-processing algorithms which enable us to increase the reconstruction quality of our defects (see the comparison of Figure 1 (a) and (b) by applying Block-Elastic-Net). However, the effectiveness of these algorithms relies on priors such as the joint sparsity of all measurements [3, 5, 7].

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