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Laser excited super resolution thermal imaging for nondestructive testing

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Summary:
The work to be presented focuses on our most recent studies to laser excited super resolution (SR) thermography. The goal of nondestructive testing with SR is to facilitate the separation of closely spaced defects. Photothermal SR can be realized by performing structured illumination measurements in combination with the use of deconvolution algorithms in post-processing. We explain that stepwise as well as continuous scanning techniques are applicable to generate structured illumination measurements. Finally, we discuss the effect of 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 the heat is mainly responsible for the fact that two defects located close to each other cannot be resolved 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 fields and are known e.g. in optics [1]. Even in non-destructive testing, SR techniques have been applied, for example in photoacoustics [2]. SR can be realized in different ways, but all these SR techniques have the same goal, namely to increase the spatial resolution (artificially) 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. Through appropriate experiments and the application of appropriate image processing algorithms to the measured data, we have been able to obtain more information in our thermal images [3,4,5].

Since laser scanning can easily be combined with thermography and is therefore of high interest for the industry in terms of non-destructive and non-contact testing [6], we conducted investigations on the applicability of SR techniques. We investigated the influence of experimental parameters like laser line width or laser pulse length on the reconstruction quality. We also analyzed the influence of image processing techniques such as the superposition of different measurements or the selection of suitable regularization parameters to optimize our reconstruction results, e.g., by using compressed sampling-based algorithms such as the iterative joint sparsity approach (IJOSP) [7].

Methods

To understand how super resolution techniques can be used in laser line thermography, it is advisable to describe the measured temperature data of the IR camera mathematically. For the reflection configuration (we measure with the IR camera from the same side where we illuminate) our temperature field can be described as follows [8]:

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

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 $\tilde{r}$.

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Within our SR studies [3,4,5] we rewrite equation (1) by using the following equation which describes temperature differences:

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

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 the exact position of illumination is in reality hard to determine, we decided to put the information about the spatial information into x whereas the temporal information that is known pretty well can be kept in A. Therefore, we talk about blind structured illumination. As structured illumination means that multiple measurements have to be performed to scan the whole sample surface, the equation (2) changes to:

$$\Delta T^m = A * x^m \quad (3)$$

All measurements m from structured illumination have in common that the same sparse defect pattern is considered. For this reason, we are using iterative joint sparsity algorithms (IJOSP) [4] to estimate x^m from the underlying ill-posed problem in equation (3) and thus, to obtain the defect pattern.

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).

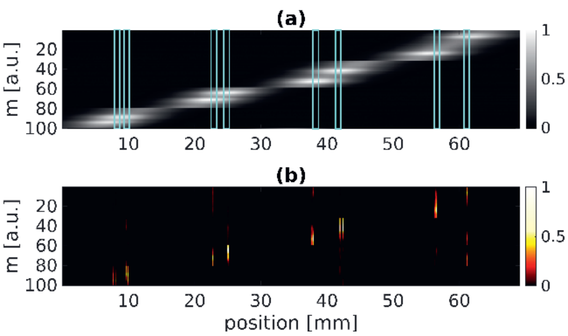

Fig 1. (a) Measured temperature difference data normalized by the maximum temperature value is shown in white. The defect pattern to be reconstructed is shown in blue and consists of four defect pairs with a distance of 0.5, 1, 2, 4 mm, respectively. We measured films with the infrared camera in transmission configuration 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) estimated x^m after applying IJOSP with Block-Fast-Elastic-Net. 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-Fast-Elastic-Net). However, the effectiveness of these algorithms relies on priors such as the joint sparsity of all measurements [3, 4, 5, 7].

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