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Detection of internal defects applying photothermal super resolution reconstruction utilizing two-dimensional high-power random pixel patterns

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Abstract

In this work, we report a new experimental approach in conjunction with 2D photothermal super resolution reconstruction. We use modern high-power laser projector technology to repeatedly excite the sample surface photothermally with varying spatially structured 2D pixel patterns. In the subsequent (blind) numerical reconstruction, multiple measurements are combined by exploiting the joint-sparse nature of the defects within the specimen using nonlinear convex optimization methods. As a result, a 2D-sparse defect/inhomogeneity map can be obtained. Using such spatially structured heating combined with compressed sensing and computational imaging methods allows to significantly reduce the experimental complexity and to study larger test surfaces as compared to the one-dimensional approach reported earlier.

1. Introduction

For a long time, the rule of thumb for active thermography as a non-destructive testing method has been that the resolvability of internal defects/inhomogeneities is limited to a ratio of defect depth/defect size ≤ 1. This limit mainly originates from the diffusive nature of thermal conduction in solids. The application of the photothermal super resolution reconstruction approach has recently allowed to overcome this limit. This approach significantly improved the width-to-depth range for which internal defects can be resolved.
In previous works, it has already been shown that the mentioned classical limit can be overcome for 1D and 2D defect geometries by scanning the test specimen using single laser spots/lines with subsequent numerical photothermal super resolution reconstruction [1, 2, 3]. These established methods use a combination of large number of sequential spatially structured illuminations, which come at the expense of additional experimental complexity, long measurement times, large data sets, and therefore tedious numerical analysis. In this work, we report on a method to significantly reduce the experimental effort by using full-field 2D laser-based illumination instead of subsequent local excitations.

2. Motivation on photothermal super resolution reconstruction

The surface temperature response of the test object, which is simplistically modelled as a thermally-thin plate, can be represented as the sum of an initial temperature distribution $T_0(x,y)$ and the spatial convolution ($*_{x,y}$) of the thermal point spread function (PSF) $\Phi_{\mathsf{PSF}}(x,y,t)$ and the heat source distribution $a(x,y)$ as follows:

$$T_{\mathsf{meas}}(x,y,z=0,t) - T_0(x,y) = \Phi_{\mathsf{PSF}}(x,y,t) *_{x,y} a(x,y) \tag{1}$$

The thermal PSF can be calculated analytically if the thermal properties of the object's material (specific heat capacity c_p, thermal conductivity λ, density ρ, diffusivity α) are known along with its thickness d, the coordinate centroid $(\bar{x},\bar{y})$, the thermal wave reflection coefficient R (typical $R \approx 1$) and the external heat flux Q as shown in Eq. 2 [4]. Further, it is assumed that the external heat flux Q can be split into a spatial distribution $a_{\mathsf{ext}}(x,y)$ of similar independent heat fluxes with amplitude $\hat{Q}$ and a spatial structure $I_{x,y}(x,y)$ as well as a temporal structure $I_t(t)$ according to Eq. 3.

$$\Phi_{\mathsf{PSF}}(x,y,t) = \frac{2\cdot\hat{\mathrm{Q}}}{c_p\rho(4\pi\alpha t)^{3/2}} \cdot \mathrm{e}^{\frac{(x-\bar{x})^2+(y-\bar{y})^2}{4\alpha t}} \cdot \sum_{n=-\infty}^{\infty} R^{2n+1}\mathrm{e}^{-\frac{(2nd)^2}{4\alpha t}} *_t I_t(t) \tag{2}$$

$$Q(x,y,t) = \hat{Q}\cdot I_{x,y}(x,y) *_{x,y} a_{\mathsf{ext}}(x,y) *_t I_t(t) \tag{3}$$

The overall heat source distribution $a(x,y)$ can then be represented as the sum of the deliberately applied external heat sources (i.e., the photothermal heat sources using the illumination) and an internal *apparent* heat source distribution $a_{\mathsf{int}}(x,y)$. This latter apparent heat source distribution originates from the fact that in active thermographic testing, internal defects with lower effusivity appear as heat sources. This is because they impede the local heat flow in a way that the temperature rise at its respective location appears as if there is an internal active heat source present. This apparent internal heat source distribution therefore resembles the internal defect structure which is to be reconstructed.

$$a(x,y) = I_{x,y}(x,y) *_{x,y} \left(a_{\mathsf{ext}}(x,y) + a_{\mathsf{int}}(x,y)\right) \tag{4}$$

By performing multiple different independent measurements $m \in [1, \dots, n_m]$ and by introducing regularizers which make use of priors related to the equation's physical nature (ℓ_1) plus the fact that the internal defect structure is constant for all measurements ($\ell_{2,1}$), the solution space can be constrained such that the severely ill-posed Eq. 1 can be inverted to extract the heat source distribution $a(x, y)$ [5]. This numerical reconstruction ansatz can be achieved using the alternating direction method of multipliers (ADMM) algorithm leading to a reconstruction $a_{\text{rec}}(x, y)$ of $a(x, y)$ and therefore the internal defect pattern as encoded in $a_{\text{int}}(x, y)$:

$$\begin{aligned} \text{minimize} \quad & f(p) + g(q) = \left\| \Phi_{\text{PSF}}(x,y) *_{x,y} p^m(x,y) - T^m_{\text{meas}}(x,y) - T_0(x,y) \right\|_2^2 + \lambda_{21} \left\| q^m(x,y) \right\|_{2,1} + \lambda_2 \left\| q^m(x,y) \right\|_2^2 \\ \text{subject to} \quad & p^m(x,y) - q^m(x,y) = 0 \end{aligned} \tag{5}$$

3. 2D random pixel pattern excitation

The recent developments in the field of digital micromirror device (DMD)-based high-power laser projectors now allow for their application within active thermographic testing. With such projectors, it is possible to project whole pixel patterns at once, which reduces the amount of measurements required to achieve homogeneous illumination of the test object on average and thus shortens the measurement time [6]. Although the available projectors feature high independent pixel counts ($\approx 10^6$), their still rather low optical output irradiances of $< 20\,\mathrm{W\,cm^{-2}}$ make it necessary to group the available pixels into larger *super pixels* in order to achieve a sufficient SNR. A representative photothermal super resolution reconstruction measurement using multiple 2D random pixel patterns as illumination source can be seen in Fig. 1.

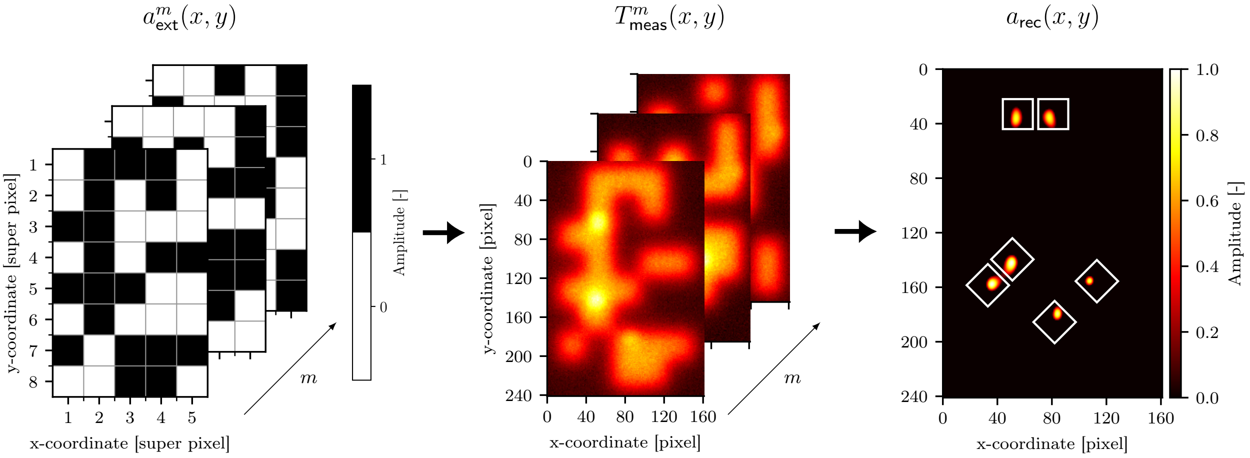

Fig. 1. *The left images shows the illumination pattern a^m_{ext} for a 2D random pixel-pattern illumination with a 5×8 grid of super pixels with a fill grade of $\beta = 0.5$, the corresponding T^m_{meas} measured surface temperature signal is shown in the middle. On the right, the reconstructed defect pattern a_{rec} from the measured data is shown. The white boxes indicate the true defect positions.*

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