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Heat source reconstruction from noisy temperature fields using an optimised derivative Gaussian filter

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HIGHLIGHTS

- We reconstruct heat sources from temperature fields using a derivative Gaussian filter.
- Synthetic temperature fields corrupted by noise enabled us to optimise the filter.
- The influence of both the dimension and the level of a localised heat source is discussed.
- Experimental fields on aluminium plates heated by electric patches were processed.
- The relevancy of the filter to reliably reconstruct heat source fields is demonstrated.

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ABSTRACT

The aim of this paper is to present a post-processing technique based on a derivative Gaussian filter to reconstruct heat source fields from temperature fields measured by infrared thermography. Heat sources can be deduced from temperature variations thanks to the heat diffusion equation. Filtering and differentiating are key-issues which are closely related here because the temperature fields which are processed are unavoidably noisy. We focus here only on the diffusion term because it is the most difficult term to estimate in the procedure, the reason being that it involves spatial second derivatives (a Laplacian for isotropic materials). This quantity can be reasonably estimated using a convolution of the temperature variation fields with second derivatives of a Gaussian function. The study is first based on synthetic temperature variation fields corrupted by added noise. The filter is optimised in order to reconstruct at best the heat source fields. The influence of both the dimension and the level of a localised heat source is discussed. Obtained results are also compared with another type of processing based on an averaging filter. The second part of this study presents an application to experimental temperature fields measured with an infrared camera on a thin plate in aluminium alloy. Heat sources are generated with an electric heating patch glued on the specimen surface. Heat source fields reconstructed from measured temperature fields are compared with the imposed heat sources. Obtained results illustrate the relevancy of the derivative Gaussian filter to reliably extract heat sources from noisy temperature fields for the experimental thermomechanics of materials.

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1. Introduction

The study of thermomechanical phenomena by means of infrared (IR) thermography is of great interest for the mechanical engineering community. With the continuous improvement of IR cameras (both in terms of measurement resolution and dimension of detection matrix), it is now possible to measure accurately temperature fields representative of physical phenomena such as thermoelastic coupling, plasticity, and phase transitions. However, the temperature variation is not the most relevant physical parameter. Indeed, a temperature field in a specimen is the consequence of several phenomena: (i) heat sources produced by the material in the specimen; (ii) heat conduction inside the specimen; and (iii) heat exchanges with the outside of the specimen. For studying the mechanical behaviour of materials, it is more relevant to analyse the heat sources produced by the material during its deformation. In practice for the measurement of heat source fields, two approaches are available in the literature:

- The first approach belongs to the framework of the so-called 'inverse problems'. It consists in minimising the quadratic error between measured temperature fields and theoretical

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temperature fields which are provided by a model. This minimisation problem is however difficult to solve. First, experimental thermal fields are always noisy. Second, IR cameras provide data on the surface of the specimen. Even for problems which are assumed to be bidimensional, measurements are often obtained in a limited zone of the specimen. In this case, the boundary conditions of the model are the experimental temperatures at the boundaries of the thermal images. Since the problem is ill-posed, regularisation methods are classically used. Several applications based experimental thermal fields provided by an IR camera have been performed, see Refs. [1–6]. For example, the approach developed in Ref. [6] is used for material parameter identification and provides a physical interpretation of various thermomechanical contributions in a semicrystalline polymer subjected to tensile loading.

- The second approach consists in directly calculating heat sources from experimental temperature variation fields using the heat diffusion equation. Important results have been obtained about the behaviour of materials with the work of A. Chrysochoos since the late 1980s (see Refs. [7–9] and references included). An advantage of this approach is that it is not necessary to know the boundary conditions of the problem in this case. However as for the first approach, temperatures are only known at the surface of the specimen. To overcome this difficulty, simple geometries are considered: plane specimens with small thickness or cylindrical specimens with small diametre for instance. It must then be assumed that the temperature is nearly homogeneous through the thickness. Heat exchanges with ambient air by convection are taken into account with a Fourier condition [10]. The main difficulty of this approach is the fact that the temperature fields are noisy. This leads to some problems in the calculation of the derivative terms of the heat diffusion equation. Some strategies have been tested in the literature: mean-square approximation, low-pass recursive filter, 'sliding' smoothing window (local averaging or mean-square approximation), Fourier series, etc. This approach has been used to study various thermomechanical phenomena such as strain localisation in steels [10,11], Portevin Le Châtelier bands in aluminium alloys [12], propagation of necking in a polyamide [13], thermoelastic effects accompanying the viscoelastic deformation process in a PMMA and a PC [14], phase transformation in shape memory alloys [15–19], stored energy during the plastic deformation process of metals (see Refs. [13,20–22] and included references) as well as fatigue of steels [23–26] and aluminium alloys [27,28]. Converting temperature fields in heat source fields is also discussed in Ref. [29], where the nondestructive evaluation of induced frictional heating in a crack in titanium is addressed. Refs. [30,31] also present experimental studies based on heat source reconstruction in vibrothermography.

The current study belongs to the second family. It relies on the use of a derivative Gaussian filter to estimate heat sources in a bidimensional specimen. We focus here only on the diffusion term which involves a second-order spatial derivative (Laplacian operator for isotropic materials). A convolution of the temperature variation fields by second derivatives of a Gaussian function is applied. The first part of the study is based on synthetic temperature fields obtained by finite differences. The influence of noise, which is a key-issue here, is taken into account. The filtering parameters are optimised in order to reconstruct at best the imposed heat source field. The influence of both the dimension and the level of a localised heat source is discussed. Obtained results are compared with another type of processing based on an averaging filter in order to highlight the relevancy of the derivative Gaussian filter compared to this more classic approach. The second part of the study presents an application to several experimental temperature fields obtained by infrared thermography. Heat sources are created with an electric heating a patch glued on the surface of aluminium specimens. The heat source fields reconstructed from measured temperature fields are compared with the imposed heat sources to assess the efficiency of the proposed method.

The paper is organised as follows: Section 2 recalls the bidimensional version of the heat diffusion equation used for heat source calculation; Section 3 presents the derivative Gaussian filter to be applied to the temperature fields; Section 4 presents the applications to theoretical temperature fields with added noise; finally, Section 5 presents an application to experimental temperature fields obtained by IR thermography.

2. Heat diffusion equation

Let us consider a rectangular plate in the (x,y) plane with small thickness along the z direction (say a few millimetres for metallic materials). The bidimensional version of the heat diffusion equation can be written as follows for an isotropic material [10]:

$$\rho C\left(\frac{\partial\theta}{\partial t}+\frac{\theta}{\tau}\right)-k\Delta\theta=s_t \tag{1}$$

where $s_t(x,y,t)$ is the heat source produced by the material and $\theta(x,y,t)$ the temperature variation from a reference state. The material parameters are the thermal conductivity k, the density ρ and the specific heat C. The parameter τ is a time constant characterising the heat exchanges by convection with air in the z direction. In this equation, symbol Δ is the Laplacian operator in the (x,y) plane, thus $\Delta\theta = \partial^2\theta/\partial x^2 + \partial^2\theta/\partial y^2$.

It is generally useful to divide Eq. (1) by ρC. In this case, the advantage is that only one thermophysical material quantity is needed, namely the thermal diffusivity $D = k/\rho C$ of the material. This leads to:

$$\frac{\partial\theta}{\partial t}+\frac{\theta}{\tau}-D\Delta\theta=s \tag{2}$$

where $s = s_t/\rho C$. This approach is used for instance in Refs. [10,18,24,27], which also consider heat sources divided by ρC. Note that the thermal diffusivity D is an input data for the processing proposed in the present study.

The heat source s_t is expressed in W/m^3 and s is in K/s. s can be interpreted as the temperature rate that would be obtained in case of adiabatic evolution of the observed system. In the following, s will be named 'heat source' for the sake of simplicity.

The heat source fields s (cause) can be deduced from the temperature variation fields θ (consequence), thanks to the left-hand part of Eq. (2). With noisy input data, the most difficult term to calculate is the Laplacian term, so we focus here on the diffusion term only: $-D\Delta\theta$. Its calculation does not involve temporal derivatives. The processing proposed in this study is designed to be applied to an image at a given time. Without altering the relevancy of the processing, we have fix some conditions of the thermal image to be processed: the steady-state temperature field resulting from a heat source field constant in time, *i.e.* $s(x,y,t) = s(x,y)$ and $\theta(x,y,t) = \theta(x,y)$. In this case, Eq. (2) reduces to:

$$\frac{\theta}{\tau}-D\Delta\theta=s \tag{3}$$

Filtering is a key-point of the technique to estimate heat source fields since the goal is to calculate spatial derivatives from noisy temperature variation fields. As recalled above, the classic route consists first in smoothing the experimental data and then in differentiating the obtained result. The idea here is to merge both stages by convolving temperature variation fields with a suitable

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