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Experimental validation of the filtering technique approach applied to the restoration of the heat source field

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ABSTRACT

The present investigation was focused on the experimental validation of a solution strategy of the Inverse Heat Conduction Problem (IHCP), based on optimal filtering of raw input data acquired by the infrared thermographic technique. The particular application here addressed regards the inverse restoration of the heat source field on a thin conductive wall. The filtering technique approach, that can be regarded as a regularization method in the sense that it is based on computing the smoothest approximated solution consistent with available data, was already successfully adopted in literature with regard to IHCPs. The aim of the present analysis is to compare the effect of different filtering techniques, namely the ideal low-pass, the Gaussian and the Wiener filter, by focusing on the optimal choice of the cutoff frequency. Basic theoretical considerations were developed in the frequency domain with the aim of identifying the optimal approach for inversely restoring the second derivative of a noisy signal. The different filters were compared by considering their application to a synthetic 1-D periodic signal and then to infrared temperature maps experimentally acquired on the rear surface of a copper thin plate on which two point heat sources were located. The noise suppression effect of the filters enabled to handle the ill-conditioned nature of the inverse problem by making the localization of the heat sources feasible. For the signal considered in the present paper, the heat sources were identified with good precision by both the Gaussian and the Wiener filter, if applied twice to the raw data. It must be observed that the particular shape of the transfer function which was derived by applying two consecutive Wiener windows, amplifies the self-adaptive capacity of the filter by making it particular suitable for denoising thermal images by minimizing, at the same time, the undesired signal attenuation effect.

1. Introduction

The reconstruction of the heat source field over a given domain represents an important issue in several engineering problems, ranging from the mechanical to the energy and electrical engineering sectors. The restoration and localization of the heat sources can be important for instance in the monitoring of the power dissipation profile in electronic devices, in the thermomechanical characterization of materials subjected to a fatigue test or in the control of nuclear power reactors. This issue is generally performed by measuring the effect of the heat source distribution, i.e. the temperature distribution over an accessible boundary wall of the system under investigation. With this regard, the temperature field can be acquired either with traditional contact sensors or, more suitably, with non-intrusive thermographic techniques, which allow to reach a high both spatial and temporal resolution. The problem, which relies on temperature measurement for estimating unknown quantities involved in the physics of a given phenomenon, is regarded as an inverse heat transfer problem [1]. In particular this problem is named Inverse Heat Conduction Problem (IHCP) which can be formulated either in steady state (SIHCP) or unsteady state (UIHCP) conditions. One of the most widely known applications is based on the measurement of the temperature response of a thin conductive wall from which the heat source field is localized and restored both in time and space (see for instance [2]).

The well known difficulties involved in inverse heat transfer problems and particularly in the IHCP, stem primarily from the fact that they are ill-posed, see for instance [1,2]. In particular the problem is ill-conditioned, i.e. it is very sensitive to small perturbations in the input data due to the well-known destructive effect of noise with regards to the estimation of the signal's Laplacian which is implied in the formulation of the local energy balance in the solid domain [3]. A great deal of intensive and very fruitful work has been devoted to the development of solution strategies of the IHCP.

The first developments in theory and application of solution approaches to inverse problems are traced back to the first half of the 20th century and to the work performed by the mathematicians of

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Nomenclature

b	background noise (°C/K)
d	plate thickness (m)
E	observation function (Eq. (22)) (K)
H	transfer function
q	overall heat flux per surface area (W/m^2)
q_g	heat source per surface area (W/m^2)
s	pure signal (°C/K)
T	temperature (°C/K)
u, v	spatial frequency (m^{-1})
u_c	cutoff frequency (m^{-1})
x, y	spatial coordinates (m)
α	heat transfer coefficient (W/m^2 K)
λ	thermal conductivity (W/m K)
σ	variance (°C/K)
Subscripts	
b	background noise
s	pure signal
T	raw temperature signal
Superscripts	
n	nth derivative
exp	experimental data
$\sim$	Fourier transform

the Russian school (in particular to the effort performed by Tikhonov and Arsenin and Alifanov [4,5]). With particular regard to the inverse heat transfer problem, the most relevant work is also due to the work developed by Beck et al. [2]. An overview of the solution techniques for inverse heat transfer problems is reported in [1].

The majority of the solution strategies of IHCP handles its ill-posed nature, and in particular the instability of the system response with respect to random errors in the input data, by reformulating the problem as a well-posed problem by minimizing an objective function, which generally expresses the squared difference between measured and estimated temperature discrete data (see for instance [6,7]). One of the most famous solution strategies belonging to this class is the regularization scheme suggested by Tikhonov and Arsenin [4] which is based on computing the smoothest approximated solution consistent with available data.

It must be observed that most of the above described "traditional" solution techniques of the IHCP are based on some more or less complex algorithms which often develop iteratively. Moreover they have been tested and validated in literature by reflecting their possible application to temperature distributions acquired with traditional contact sensors and therefore characterized by a limited number of both input and output variables [2]. On the contrary, their application to problems characterized by a high number of degrees of freedom is often impracticable. The computational requirements for instance of the Tickhonov's regularization technique are very onerous in handling the solution of the IHCP if applied to infrared thermographic data, since the excessive computational cost of the solution algorithm, as observed in [8].

With particular regard to the problem of heat source field reconstruction under the IHCP approach, several strategies have been suggested. The conjugate gradient method coupled to the finite element method has been applied in [9,10] for estimating the time wise varying strength and/or location of plane or line heat sources.

Yang [11] suggested and validated an algorithm based on the finite element method to discretize the spatial coordinate and on the finite difference method to discretize the temporal coordinate for determining the strength of two sources having known locations, by particularly considering the effect of the different shape and reciprocal distance of the two sources. The boundary element method has been applied for estimating multiple point and line heat sources in both 2-D [12,13] and 3-D cases [14]. The same solution methodology is applied under a parameter estimation approach in [15]. A two-step optimal regularization procedure for estimating both spatially and time-dependent heat source fields was presented in [16] by focusing on its application to the thermomechanical characterization of materials by adopting infrared thermal images. With regard to the same applicative field, a method to identify the heat source distribution from infrared images and based on the projection of the temperature field on spectral basis was presented in [17]. The IHCP in a multilayered slabs with heat sources is considered also by Pailhes et al. [18] under the thermal quadrupole formulation.

A competitive and challenging approach to handle the ill-posed nature of the IHCP, and in particular the instability of the system response with respect to random errors in the input data, is represented by the possibility of treating the raw input temperature data by some suitable filtering technique. Under this approach the direct solution of the inverse problem is in principle feasible [19,20].

This approach can be regarded as a regularization method in the sense that it is based on computing the smoothest approximated solution consistent with available data [21]. The same philosophy is under the mollification method proposed by Murio [22] who developed a data smoothing techniques to identify unknown coefficient and functions in ill-posed system of partial differential equations. In particular the method presented by Murio [22] exploits the averaging property of the Gaussian kernel to smooth noisy data. Another well known approach widely adopted when dealing with discrete ill-posed problems is the truncated singular value decomposition method, that enables to filter out the high frequency fluctuation in raw input data, by properly conditioning the given inverse problem (see for instance [21–24]).

A filtering technique was explored by Qian and Fu [25] by adopting a method based on the truncation of the high frequency components of the signal.

It is important to observe that the filtering approach to IHCPs can be considered suitable only for input signals represented by spatially and/or temporally highly resolved temperature maps, while it appears not practicable for signals represented by a limited number of input variables. This possibility is then actually offered only if the input data are acquired by remote and non-contact thermal monitoring experimental techniques, like the thermochromic liquid crystals technique and the infrared thermographic technique.

The problem of infrared image enhancement has been the object of several research works: Ilk et al. [26] explored the effect of Laplacian filter while Voskoboinikov [27] suggested the use of descriptive splines for the differentiation of noisy data. Although this, rarely the possibility of adopting signal denoising techniques to preprocess the temperature data to directly restore from them unknown information has been attempted. More particularly, the filtering techniques suitable for this task must have a specific behavior with respect to the restoration of the second derivative