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3D heat diffusion simulation using 3D and 1D heat sources – Temperature and phase contrast results for defect detection using IRT

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ABSTRACT

Infrared thermography (IRT) has proven to be a powerful non-destructive technique and it has been successfully used for detecting defects in a wide range of applications and sectors. Numerical modeling of heat transfer and diffusion in the presence of defects combined with experimental IRT results may be used both to detect and characterize existing defects with specific geometries and depths. However, the three-dimensional (3D) nature of defects combined with the need to simulate heat transfer and diffusion phenomena in transient regime often presents many challenges for researchers. The study presented in this paper is motivated by such difficulties and is intended to contribute to the interpretation of quantitative data results collected in experimental defect detection IRT tests and help with the definition of IRT experimental set-up parameters.

In this study, 3D heat diffusion by conduction in the proximity of a 3D defect is modeled using a boundary element method (BEM) formulated in the frequency domain. The defect is a crack lodged in an unbounded solid medium with null thickness. In order to overcome difficulties that occur in the presence of null thickness elements, the BEM formulation was written in terms of normal-derivative integral equations (TBEM) and known analytical solutions were used to solve the resulting hypersingular integrals. The focus of this paper is to study the influence using either a 3D (point) energy source or a 1D (planar) energy source in heat diffusion simulations performed for IRT defect detection studies. Heat field and thermal wave phase results were computed in the presence of a defect and for when there is no defect present and a comparative analysis of the results obtained for a point and a planar source was carried out. In order to contribute to defects characterization studies, the influence of the crack's characteristics such as its size, shape and placement (depth and position) was analyzed using a phase contrast approach. Other features that may be relevant in IRT experiments, such as the nature of the stimulus provided and its distance from the surface were also studied. The major findings achieved from varying those parameters are presented in the conclusions.

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1. Introduction

Analyzing thermal pattern images obtained using infrared thermography (IRT) has shown to be an effective non-destructive testing (NDT) technique which is used in many sectors for many applications, including the detection of hidden defects. Defects appear as anomalies in the thermal patterns of thermographic images since their presence affects the heat and moisture diffusion phenomena. Passive IRT studies are performed with materials in their natural thermal state and are mostly done using a static approach. However if a temperature gradient that allows the identification of anomalies in the thermal patterns is not naturally present, it may be necessary the use an additional heat source in order to produce it. This technique is known as active IRT [1]. Additionally, if results are obtained in a transient regime, and the nature of the heat source generated in active IRT is well defined, a quantitative characterization of defects may be performed by solving heat transfer problems using thermographic data. For this reason, active IRT has been used in NDT in a great number of areas, including in civil engineering [2]. In particular, the technique has been successfully used to test the integrity of composites and structures, having detected surface moisture and located defects in concrete composites up to a depth of about 10 cm, as reported by Wiggenhauser and Maierhofer [3].

Fig. 1 is a general representation of the experimental apparatus for an active IRT test. A known thermal wave generated by a heat source (stimulus) is applied to a test specimen, leading to heat flow inside it. The reflected thermal wave is altered by defects inside the specimen, which produces disturbances in the temperature patterns on the surface. These are recorded by the IRT camera as a function of time. Data is stored in a computer and can then be subject to a range of processing techniques (data analysis).

A number of active IRT techniques have been categorized, depending on the thermal stimulation scheme used to produce a relevant temperature gradient on the surface of a test specimen, and on the data processing technique employed. In [4] Maldague considers several methods, such as pulse thermography, step-heating and lock-in thermography. Pulse thermography (PT) is one of the most popular thermal stimulation methods. It consists of briefly heating a test specimen and recording its temperature decay curve. Since a subsurface defect reduces the diffusion rate of the thermal front propagating by diffusion under the surface, the presence of such defect appears as an area of higher surface temperature. PT data results are thermal images corresponding to the mapping of the emitted thermal infrared power. In step heating (SH), a long heat pulse is generated and the increase in surface temperature is monitored. In lock-in thermography (LT), modulated heating at frequency ω generates a temperature field inside the material (near the surface), which is recorded by the equipment. This allows the observation of both the amplitude and phase of the resulting thermal waves. In LT experimental results, both amplitude and phase images are available. Phase images have the added advantage of being relatively independent of local optical and thermal surface features. Each of the various schemes has its own advantages and limitations and choosing the most suitable approach depends on the intended application. In any case, several heat distributions are possible: point inspections using laser or focused light beams; line inspection using line lamps, heated wires, linear air jets or a scanning laser, and surface inspections in reflection or transmission [5].

Ibarra-Castanedo et al. [6] explored various data analysis methods for processing raw thermal image results in subsurface defect detection and characterization studies. Maldague and Marinetti [7] first introduced pulsed phase thermography (PPT) as a processing technique which combines the advantages of both PT and LT. Test specimens are pulse-heated but thermal waves are unscrambled by performing the Fourier transform of the temperature decay and enabling the computation of phase images [7]. More recently, Arndt [8] introduced the term square-pulse thermography (SPT) in the frequency domain in an adaptation of PPT for civil engineering applications. Arndt concluded that SPT is an ideal approach for IRT use in civil engineering because phase

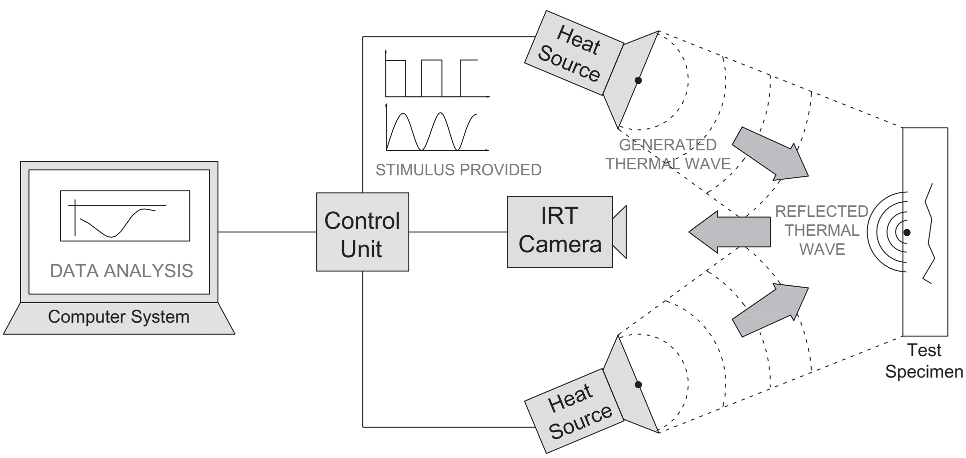

Fig. 1. Schematic representation of an experimental setup for an active IRT test.