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Active and eddy current pulsed thermography to detect surface crack and defect in historical and archaeological discoveries

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ABSTRACT

The present paper describes the results of an experimentation concerning the joint use of active thermography and eddy current pulsed thermography to assess the conservation state of historical and archaeological discoveries. The preservation of historical and archaeological heritage is today an open issue due to the amount of finds and to the costs of the current methodologies and technologies used. As a consequence, interventions are made only when a deterioration process is in progress. The use of non-invasive techniques is essential for such applications in order to not compromise the integrity of the find.

Thermography has been used to measure the thermal response of a metallic historical artifact (an iron oil lamp) during the application of thermal solicitations. The authors propose the use of a hybrid technique combining the standard active thermography with the eddy current pulsed thermography. This hybrid technique is non-invasive and contactless and allows to detect surface cracks and defects which are not visible at naked eye. Results have shown clearly how the proposed thermographic technique allows to improve the effectiveness of the standard techniques to detect surface defects. The defects are more easily detectable because of the more accentuated contrast and better resolution of the thermographic images. The final aim of the paper is to describe how this improved technique can be used to diagnose, monitor and preserve the conservation state of historical or archaeological discoveries.

1. Introduction

Artifacts, sculptures, ruins, historical buildings, archaeological sites and discoveries are an important part of worldwide cultural heritage to be preserved. Their periodic maintenance and monitoring are crucial to assure the preservation for centuries and centuries. Italy has a wide cultural heritage of historical artifacts and archaeological discoveries. Their conservation represents a significant time-consuming activity which entails huge economic costs.

Transducers, sensors and measurement instrumentation are today widely used in several applications concerning the monitoring of archaeological discoveries integrity [1,2]. Nevertheless several perspectives and open research problems have to be investigated such as data processing, sensor failure and reliability, interface and signal treatment, standardization, fault-tolerance, maintenance, calibration and traceability issues. Therefore, this is an interesting application field for researchers and experts who deal with these topics. In addition, not always the use of sensors is applicable or feasible, due to the extension of the site or to the development costs. For this reason, alternative techniques are today proposed and investigated in order to assess the state of conservation of finds. Some of such techniques are used in other sectors so as the medical one: tomography, X-ray, etc. Currently the main challenge is to define non-invasive, low-cost and effective techniques which are able to scan large surface in one snapshot.

This paper aims to describe the potentialities of the joint use of two thermographic techniques: active thermography and eddy current pulsed thermography, [3–5]. Since the latter technique is also classified as an application of active thermography by means of the use of a specific excitation system, to avoid misunderstandings, the term "active thermography" refers to the basic technique where a simple heat flow is used to excite the test object, [6]. By using an infrared thermal camera, it is possible to measure the electromagnetic radiation emitted in the infrared spectrum. The emitted infrared energy is a function of the object temperature. In this way, the processing unit converts the intensity of infrared radiation into temperature values so to generate an infrared image. The analysis of the thermal response over time allows the user to characterize the presence of irregularities or defects in the surface layer of the tested object. Thermal cameras with high accuracy

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and resolution permit to measure the slightest changes and differences of temperature with a thermal sensitivity even of 15 m K. Advanced cameras can capture thermal images with high resolution of 1280 × 1024 pixels and with a frame rate of about 100 Hz. Highest performances can be obtained with the use of thermal camera mounting an uncooled microbolometer detector.

Due to its history, Italy is the country with the richest amount of historic/archaeological and architectural sites and finds. Consequently, thermography can be considered as an alternative or complementary technique in respect to the invasive ones, [7–12]. The proposed hybrid technique allows to improve the reliability of two different methodologies to diagnose non-invasively the conservation state of finds. In detail, the use of the standard techniques is defective in detecting very small cracks or surface defects. Therefore the authors intend to prove that the proposed thermographic technique allows to improve the effectiveness of the two methods by increasing the contrast and resolution of the thermographic images. The proposed experimentation concerns a metallic historical artifact. An iron oil lamp has been tested to detect defects and cracks on its surface, [13]. Thermal imaging analysis has allowed us to investigate the object integrity without any risk for it so to preserve its state, [14,15]. Experimental results have shown clearly the presence of defects due to iron corrosion caused by an unsuitable conservation of the artifact for several years.

The paper is organized as follows. In Section 2, the theory of the active and eddy current pulsed thermography is described. The setup and the used test bench are described in Section 3. Section 4 describes the used measurement procedure and reports the experimental results. Finally, conclusions are outlined in Section 5.

2. Thermography and thermographic techniques

Any object, having temperature over the absolute zero, is able to absorb or emit thermal energy in Infrared (IR) range, [16]. IR spectral range is part of the electromagnetic spectrum. Its wavelengths are within the interval 0.78 μm–1 mm. The radiance W depends on two main parameters: the wavelength of radiation λ and the thermodynamic temperature T of the object. The Planck's Radiation Law regulates such dependence according to the equation:

$$W(\lambda,T) = \frac{2\pi hc^2}{\lambda^5}\left[\exp\left(\frac{hc}{\lambda kT}\right)-1\right]^{-1} \quad (1)$$

where h is the Planck constant, c is the velocity of light in vacuum, k is the Boltzmann constant.

The mechanism that allows infrared energy to be emitted or absorbed depends on the atoms and molecules movements. In detail, molecules may move in specific directions and vibrate, rotate, twist along an axis. This mechanical interaction allows the infrared energy to be transferred or absorbed. As an example, Fig. 1 shows three possible atom interactions.

Such interactions intensify with the increase of the object temperature. As a consequence, higher temperature values are cause of greater interactions, consequently the object exchanges a greater amount of thermal energy. A thermal IR camera is able to measure the object radiance pixel by pixel. By means of integrated algorithms, each radiance value is converted into temperature value, consequently the captured scene is depicted by a thermometric IR image.

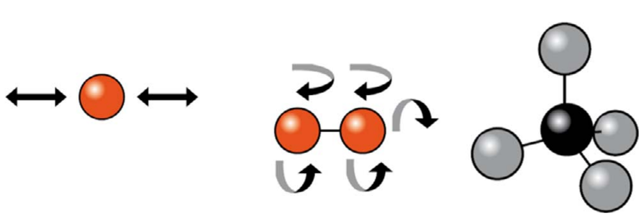

Fig. 1. Possible atom interactions.

Two important parameters have to be known: the reflected temperature and the object emissivity. In order to quantify the amount of radiated energy in relation to the incident radiation energy, the emissivity ε_λ can be estimated by the equation:

$$\varepsilon_\lambda = 1-\tau_\lambda-\rho_\lambda \quad (2)$$

where τ_λ is the transmittance and ρ_λ is the reflectance of the object.

Depending on the specific application and scope, different thermographic techniques have been defined. The first classification concerns the passive and active thermography. Passive thermography is the most common technique. The radiance of the object is simply measured by using a thermal camera. This methodology permits just to analyse the temperature gradient distribution over the object surface. No physical interaction or excitation is performed. The basic active thermography technique needs an external thermal excitation system in order to increase or decrease the object temperature by exchanging simply heat. In this way, it is possible to analyse the thermal response of the object over the time. This technique allows to obtain relevant information about the object since the parts with structural irregularities (changing thickness, corrosion, different materials, cracks, defects) have a different thermal response over the time.

Further, advanced active thermography techniques are today used for specific applications: lock-in IR thermography, spectral thermography and eddy current pulsed thermography. The first method uses external thermal excitation systems (halogen lamps, flash lamps, ultrasound, laser, mechanical excitation source) to heat the object. The thermal image acquisition is synchronized with the exciting signal. Amplitude and phase of thermographic image are processed by using specific algorithms to extract detailed information about the object properties. The second method takes advantage from the different spectral response of any substance [17,18]. Spectral filters allow to select specific wavelength ranges of infrared radiation. As a consequence, since, any substance emits or absorbs infrared energy only in a restricted IR sub-range, this property can be used to characterize the thermal contribution of the specific substance detecting its presence. The last method uses a high frequency magnetic field irradiating a conductive object under inspection [19,20]. Eddy currents are generated over the object surface to heat the excited part [21]. In presence of a defect or a crack, by means of a thermal image, it is possible to observe a different temperature distribution around the defect. This last method is mainly used to detect cracks in metallic components [22,23].

The specific application case concerns a metallic artifact. The joint use of the basic active thermography and the eddy current pulsed thermography is proposed in the following. The aim of the experimentation is to prove the major accuracy and selectivity of this hybrid technique in respect to each methodology.

3. The application case and description of the test bench

The proposed application case concerns an ancient iron oil lamp, see Fig. 2. The metallic artifact was discovered in the subsoil of a rural area. It is supposed that its origin is dated back to the last half of the 1800s. By considering the artifact state, probably it was underground for several years before its discovery. Although at a first look, outwardly the artifact looks in fair conditions, the exposure to high levels of humidity and to bad weather conditions has corroded its structure. Fig. 2 shows clearly the surface of the lamp entirely covered by rust. No further and evident surface defects are visible at naked eye. Table 1 summarizes the main characteristics of the examined artifact.

The experimentation has been carried out to analyse the thickness irregularities and the conservation state of the test object by detecting possible surface cracks and defects. The used test bench consists of a measurement system, a thermal conditioning system and an excitation system generating eddy currents. In detail, the measurement system is the *Thermal Infrared Camera FLIR x8400sc* used to record the thermal response over time of the test artifact. It is a high performances thermal