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# Study of the causes of uncertainty in thermoelasticity measurements of mechanical components

Roberto Marsili*, Gianluca Rossi, Emanuela Speranzini

*Department of Engineering, University of Perugia, Via Duranti, 93, 06125 Perugia, Italy*

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## ABSTRACT

Thermoelastic stress analysis (TSA) is a contactless technique for measuring stress distributions in mechanical components stressed by dynamic loads. The application of TSA was proposed since more than twenty years ago. In many papers available in literature thermoelasticity systems are used not to perform quantitative measure but only for non-destructive evaluation of structural integrity of components, joints etc. In the present paper a systematic experimental work is carried out in order to better understand what is possible to measure on simple specimen of mechanical components. This work describes the characteristics, analyses the main causes of uncertainty and illustrates a series of operative methods for reducing its effects. More specifically, the effects of the angle of view between the thermographic camera and the surface of the object are studied, along with those due to the heat transmission by conduction between the various parts of the thing being measured according to the stress frequencies. The analyses, both theoretical and experimental, are aimed at defining the operational limits and optimal measurement and test conditions in relation to the measurement uncertainty that is considered tolerable in the specific application.

## 1. Introduction

Thermoelasticity is a technique used to measure the state of stress that is not destructive and is based on the capturing of infrared images. Infrared radiation (IR) is in fact that which is of interest in the study of thermoelasticity, since the radiation emitted by bodies at room temperature falls precisely within the range of the spectrum from 0.76 to 1000 μm; only at temperatures above 800 K do objects begin to emit radiation in the visible range in appreciable amounts [1]. Depending on the degree of molecular agitation, the IR spectrum can be divided into three main regions: near IR (wavelengths from 0.78 to 1.5 μm), mid IR (1.5–20 μm) and far IR (20–1000 μm). The most interesting range for non-destructive thermographic tests is the near and mid IR, in the infrared radiation band with wavelengths between 0.75 and 14 μm. The measurement of this radiation allows one to obtain the surface temperature of the bodies, and therefore by using a thermal camera it is possible to trace the thermal map of the "scene" framed through the interpretation of the radiation perceived by the detector, which is the sensitive element [2,28,29].

Thermoelastic infrared analysis can be applied to the study of materials and structures mainly in two ways: thermoelastic stress analysis, to visualize and measure stresses in structural elements under stress [3], and in non-destructive tests to obtain information and images regarding defects (the defect generates an alteration of the thermal field) such as thermal irregularities caused by cracks [4], bonding, gaps, material discontinuities, porosity, and delamination as in the case of composite materials [5–7], which may compromise the mechanical strength of a structure [27].

One of the main advantages of this technique is that it makes it possible to analyse the temperature of anybody without coming into contact with it, i.e. in a non-invasive manner, allowing the measurements to be repeated over time. Moreover, it requires no surface preparation (except in the case of shiny metal surfaces), it allows the inspection of large surfaces in a short time, it does not use harmful radiation and, in contrast to X-rays, as it can work by reflection, it does not require the body to be accessible from both surfaces. The technique is applicable in a wide variety of fields and situations: in the mechanical industry [18,21,22], aeronautics [16,23], automotive [12], components and structures can be analysed both in production and in use [8]; in civil buildings it is highly valued because it is a contactless, non-invasive, is easy-to-use investigative technique for the historical and artistic heritage [9,10].

In thermoelastic analysis, once the surface temperature of the loaded structural element has been measured, it is possible to directly determine the state of stress through the stress invariant, which is the sum of the main stress components. It has been shown that it can

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* Corresponding author.
*E-mail address:* roberto.marsili@unipg.it (R. Marsili).

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provide quantitative results in accordance with the values provided by strain gauges [30], compared to which this system has the advantages of being able to inspect the entire visible surface of a structural element, of having greater spatial resolution in reading the stress concentration peaks, and of not having complex shape problems that could prevent the attaching of the instruments. However, in a thermoelastic system, there may be several causes of measurement uncertainty, above all the many interference inputs unrelated to the thermoelastic effect, which vary the surface temperature of the stressed component.

In this work the main causes of uncertainty [31] are analysed and a series of operative methods for reducing its effects are illustrated, in accordance with standard normative [15,26]. More specifically, the effects of the angle of view between the thermal camera and the surface of the object are studied, along with those due to the heat transmission by conduction between the various parts of the object being measured according to the stress frequencies [33,34]. The theoretical and experimental analyses performed made it possible to define quantitatively the operational limits and optimal conditions for measurements and tests for the most common usage situations, in relation to the measurement uncertainty that is considered tolerable in the specific application.

## 2. Theory of thermoelastic measurement

The thermoelastic effect is the variation in temperature generated on the material of a mechanical component when it is stressed by dynamic loads [19,20,24]. This physical phenomenon is well-known for gases, which vary in temperature if subjected to a change in pressure. The thermoelastic effect is generated in solids by the first (spatial) invariant of the stress $\sigma$, which on the surface of an object can be calculated as the sum of two stresses that are in orthogonal directions from each other [25]. A variation in the time $\Delta\sigma$ of the first invariant generates a variation in the time of the temperature $\Delta T$ which can be obtained, through a series of hypotheses (material is homogeneous, linear, isotropic, etc.), from the classic equation [1,17]:

$$\Delta\sigma = -\frac{\rho c_p}{\alpha}\frac{\Delta T}{T} \tag{1}$$

where $\rho$ is the density of the material, $c_p$ is its specific heat, and $\alpha$ is its thermal conductivity. Thus it is possible to determine the stress condition of a solid body based on the detection of this temperature variation [35]. It can be calculated from Eq. (1) that, for common steel, a stress variation of 1 MPa corresponds to a temperature variation of about 1 mK, and a stress variation up to its yielding point corresponds to a temperature variation of about 0.2 K [13,14]. Therefore the temperature variations produced by the thermoelastic effect must be measured within a small range with a very high resolution. To achieve this, low-noise thermal sensors are used along with the lock-in technique in processing the output signal from the temperature-sensitive elements, as is better explained in following. In order to obtain a contactless measurement technique for stress maps, a thermal camera may be used for the detecting of temperature variations. Thermal cameras are known, however, to be sensitive to thermal radiation, which in turn is related to temperature by the laws on radiation, by emissivity, by the surface characteristics in general, and by the angle from which it is observed. For example, a grey body with absolute T temperature generates an irradiance J, given by the well-known equation:

$$J = \alpha\sigma_0 T^4 \tag{2}$$

where $\alpha$ is the emissivity of the body (supposedly grey); T is its absolute temperature; $\sigma_0$ is the Stefan-Boltzmann constant. If T varies in time by $\Delta T$ from the previous equation, a corresponding variation in the thermal output emitted $\Delta J$ can be determined. In a thermal camera this variation in thermal radiation is collected by an infrared optical system characterized by an aperture with diameter D and a focal length f. If the measurement surface that emits the thermal power is at an infinite distance from the optical system, and the infrared sensor upon which the radiated energy converges has a diameter of $d'$, then the radiant thermal power $\Delta J_{DETECTOR}$ arriving at the sensor is (from [2])

$$\Delta J_{DETECTOR} = \frac{D^2 d'^2}{4f^2}\Delta J \tag{3}$$

One great advantage to using a thermal camera is the absence of perturbations in the temperature range, and thus in the stresses to be measured. Another strong point for a thermal camera is the high response speed to dynamic inputs. The resolution that can be obtained, however, is limited by the noise level of the best infrared (IR) sensors available, which in the best conditions is rarely less than the thermal equivalent of 10 mK. However, in the development of the thermoelastic measurement technique, it was possible to solve this problem by adopting special methods for processing the signal of the IR sensors, correlating their output with the load signal, making use of the well-known lock-in amplifiers technique. This has made it possible to reduce the effects of noise and to achieve a high thermal resolution – obviously only for the measurement of average values of thermal fluctuation amplitudes. To complete the picture of the main relationships of a thermoelastic measurement chain, the typical expression of the signal-to-noise ratio of the IR sensors is given, based on the parameter $D^*$, commonly defined as the signal-to-noise ratio when the sensor is affected by 1 W of power, it has a sensitive area of 1 $\mathrm{cm}^2$, and the noise is measured with a bandwidth of 1 Hz. The noise level in equivalent thermal power can thus be expressed as:

$$NEP = \frac{d'\Delta f^{\frac{1}{2}}}{D^*} \tag{4}$$

For an evaluation of the main components of the signal-to-noise ratio of a thermoelastic system, the following expression can be written, which shows how the main parameters affect the infrared optical system, the object being measured and the measurement system:

$$S/N = \Delta J_{DETECTOR}/NEP = \frac{D^2 d' D^*}{4f^2\Delta f^{\frac{1}{2}}}\Delta J \tag{5}$$

A classic thermographic system suitable for measuring the temperature distribution over the surface of an object generally does not allow a measurement of its oscillation amplitude with the degree of resolution normally required to apply the thermoelastic principle. Thus it was necessary to develop special thermographic instruments. Specific hardware and software is used that allow a thermal camera to capture and process successive thermal images repeatedly and synchronously, and to store only one that represents the average amplitude of variation over time of the temperature on the points of the surface of the object framed. This type of system is called a differential thermographic camera. Due to the difficulty of knowing all the parameters of the previous expressions, and especially the emissivity of the object's surface, its dependence on the wavelength of the thermal radiation emitted, its dependence on the angle of view, and how thermal exchanges have an effect, in practice the system is calibrated for a direct comparison with the stresses measured in one point of the mechanical component. The strain gauge technique can be used to determine the linear deformations $\varepsilon_x$ and $\varepsilon_y$ in two perpendicular directions x and y in a small area of uniform stress. The calibration factor $k$ can thus be defined as follows

$$k = \frac{\sigma_x + \sigma_y}{S_{avg}} \tag{6}$$

where $S_{avg}$ is the average spatial output of the grey level of the differential thermographic camera pixels that measure the temperature fluctuation amplitude (or rather, the irradiation $\Delta J$) in the area of application of the strain gauges. From the known constitutive equations we get the following expression for k: