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Error analysis on measurement temperature by means dual-color thermography technique

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ABSTRACT

Dual color thermography is a non-contact measurement temperature technique used mainly when the emissivity of surface is unknown; it is based on ratio of monochromatic emissive power calculated by means Planck's radiation equation and allows measuring the temperature of gray body surface objects without being assigned their emissivity and without approximations.

For real surfaces, the emissivity varies with the temperature of surface as well as the wavelength and the direction of radiation. In this case, the dual color thermometry is executed by equipping the IR camera of two narrow band pass filters, so as to consider the surface emissivity of a quite constant value. This allows calculating the ratio between the radiative fluxes of the two different emission wavelengths that is almost independent to the surface emissivity.

One of the crucial factor in this technique is the choice of the two narrow filter wavelengths. In fact the measurement errors depends directly on the two wavelengths and the variation of spectral emissivity related to the wavelength chosen and it also depends inversely on distance between central value of filters.

In this paper, the authors have developed and validated a mathematical model of experimental setup to measure object surface temperature by means IR thermo-camera. This mathematical model was used to quantify the temperature measurement error in the dual-color technique. A novel correlation to estimate temperature measurement error was provided.

1. Introduction

Dual color infrared technique is a non-contact method of temperature measurement used mainly when the surface emissivity is unknown; it is based on ratio of monochromatic emissive power calculated by means Planck's radiation equation [1]; this technique allows measuring the temperature of gray body surface objects without being assigned its emissivity and without approximations.

For real surfaces, the emissivity varies with the temperature as well as the wavelength and the direction of radiation.

Therefore, the emissivity is one of the most prominent sources of uncertainty in infrared measurement techniques. An accurate temperature measurement therefore requires knowledge of the object's emissivity. Different approaches to reduce the influence of the emissivity on temperature measurement are discussed in the literature [2]. But generally, there are neither data on wavelength variation with temperature and methods that assure to limit the uncertainty in temperature measurements. The determination and estimation of the emissivity or implementation of new techniques emissivity free are major challenges for researches.

For example, it has been shown by Hagqvist et al. [3] that a narrow wavelength radiation pyrometer can be calibrated with type S thermocouples for temperature measurements of Ti–6Al–4V up to 1550 K using the proposed strategy. The resulting temperature uncertainty is less than 2.5%, which is considered as sufficient, especially when regarding the low value of emissivity. Purpura et al. [4], have proposed a methodology for the spectral emissivity measurement by means of a single color pyrometer providing a semi-empirical formula that allows to know the actual emissivity value of the sample's surface for whatever emissivity value set up on the pyrometer.

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Magunov [5] has used theoretical studies based on knowledge of multispectral methods to find the emissivity of a material, while Paradis et al. [6] have used sample levitation methods. As described by Brandt et al. [7] there exist emissivity reference paints, applied on object's surfaces, with specified emissivity suitable for high temperature applications in the radiation fields: a direct measure of the surface emissivity can be taken from the reference paint emission, while an indirect emissivity measure may be obtained by means of a reference paint applied to the interest area to be measured and comparing the radiation from the uncoated surface with the radiation from the reference paint.

Many techniques which realize non-contact high temperature measurements are often restricted to observations of objects of known emissivity. Indeed if the body to be controlled behaves as a black body, all the devices inferring the "true temperature" from the body radiation are accurate and reliable. On the other hand, when materials exhibit behavior different from the black body, emissivity compensations need to be done. Therefore, in case of a known emissivity, the spectral system (single wavelength) is preferentially used, for gray body (constant emissivity) a bicolor system is more likely to be utilized. For every other case the assumptions about the emissivity variations such as dependence from wavelength and the temperature have to be considered.

The use of two or more wavelengths (multicolor pyrometer) can be useful to obtain the elimination of the emissivity [8] and providing the ratio between emissivity values in different spectral regions. Yamada et al. [9] have proposed a tentative system (applying two-color thermometry) that provides a thermal image of objects with different emissivity values without being assigned their emissivity, obtaining results more accurate than the traditional thermo camera.

Researchers have adopted the use of dual-wavelength (or ratio) thermometry, in order to avoid the error in temperature measurements due to the uncertainty in the emissivity value. For a gray body, the emissivity is constant over the entire spectrum and the ratio of radiation intensities between different wavelengths will be a function of temperature only. Ueda et al. [10,11] and Muller et al. [12,13] developed a fiber-optic dual-wavelength, the first ones using two detectors linked to an optical fiber to measure temperature of the rake and flank faces and the second ones to measure temperatures on the chip and the work piece during high speed machining, both assuming the hypothesis of gray body behavior. Narayanan et al. [14] used dual-wavelength thermometry by switching between two different band-pass filters, 3.16–3.8 μm and 4.31–4.95 μm, to map the temperature distribution over the chip–tool interface. It is often argued that, although the gray body assumption is not valid for metallic surfaces, through the choice of appropriate two wavelengths, very close to each other, the spectral dependence of emissivity can be neglected, but in this case the dependence of the radiation intensity ratio with temperature will be insensitive and the effect of random noise in the signal of each sensor detector on the error in measured temperatures will be more significant [15].

The crucial and most interesting part of this paper regards the development of a mathematical model to evaluate analytically the effective radiation that reaches the camera sensor when the measurement of temperature of a body is performed. As you will see the model will be able to reproduce the experimental data obtained in the laboratory. The authors have validated the mathematical model (for wavelength in the middle infrared) through the experimental data obtained in the laboratory with the calibration of the FLIR SC5000. This mathematical model has been used to perform a theoretical analysis which has as aim to quantify the error committed in the temperature measurement by technique dual-color with respect to its actual thermal state. In particular, the temperature error due to the dual color technique will be evaluated as function of: spectral emissivity $\varepsilon(\lambda)$, spectral emissivity variation $\Delta\varepsilon = \varepsilon_{\lambda 2} - \varepsilon_{\lambda 1}$, wavelength λ and central wavelength distance of the couple filters $\Delta\lambda$ for each considered temperature value, T_{actual}.

2. Principle of dual colour thermometry

The non-contact temperature measurement approach is based on the detection of monochromatic directional intensity of radiation $\boldsymbol{E}_\lambda$ (Fig. 1). The spectral density of radiance emitted by surface with a temperature T_{obj} and emissivity $\varepsilon_{\lambda,obj}$ is given by the Planck's distribution function (Eq. (1)):

$$\begin{aligned} E_\lambda(\varepsilon_\lambda, T_{obj}) &= \varepsilon_\lambda(\overleftarrow{\varphi}, \lambda, T_{obj}) E_{n\lambda}(T_{obj}) \\ &= \varepsilon_\lambda(\overleftarrow{\varphi}, \lambda, T_{obj}) \frac{C_1}{\lambda^5 \left(\exp\left(\frac{C_2}{\lambda T_{obj}} \right) - 1 \right)} \end{aligned} \tag{1}$$

where

- $C_1 = 1.191 \cdot 10^8$ W μm^4 m^{-2} sr^{-1} (Planck's radiation constant)
- $C_2 = 14{,}388$ μm K (Planck's radiation constant)
- $\overleftarrow{\varphi}$, direction of radiation E_λ
- E_λ, monochromatic directional intensity of radiation (W μm^{-1} m^{-2} sr^{-1})
- $E_{n,\lambda}$, black body monochromatic directional intensity of radiation (Wμm^{-1}m^{-2}sr^{-1}).

Dual-color thermography technique was based on the ratio of the monochromatic intensity of the radiation, obtaining the Intensity Radiation Ratio (IRR) value (Eq. (2)):

$$\mathrm{IRR}(\lambda_i, \lambda_j, T_{obj}) = \frac{\varepsilon_{\lambda_i} E_{n,\lambda_i}(T_{obj})}{\varepsilon_{\lambda_j} E_{n,\lambda_j}(T_{obj})} = \frac{\varepsilon_{\lambda_i} \frac{C_1}{\lambda_i^5 \left(\exp\left(\frac{C_2}{\lambda_i T_{obj}} \right) - 1 \right)}}{\varepsilon_{\lambda_j} \frac{C_1}{\lambda_j^5 \left(\exp\left(\frac{C_2}{\lambda_j T_{obj}} \right) - 1 \right)}} \tag{2}$$

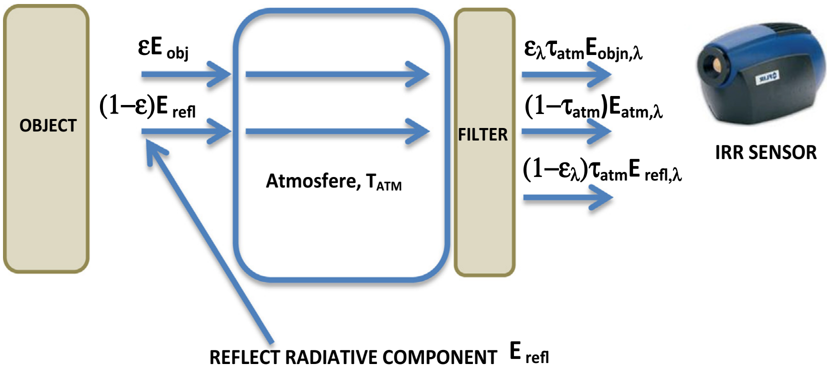

Fig. 1. Radiative contributions on thermal-camera.