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Determining directional emissivity: Numerical estimation and experimental validation by using infrared thermography

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HIGHLIGHTS

- The directional emissivity is estimated using finite element modelling.
- A numerical model is made of the reradiation on a concave surface.
- Thermography can find metal oxidation below paintings on complex surfaces.
- The use of FE modelling improves temperature measurements of curved surfaces.

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ABSTRACT

Little research has examined that inaccurate estimations of directional emissivity form a major challenge during both passive and active thermographic measurements. Especially with the increasing use of complex curved shapes and the growing precision of thermal cameras, these errors limit the accuracy of the thermal measurements. In this work we developed a technique to estimate the directional emissivity using updated numerical simulations. The reradiation on concave surfaces is examined by thermal imaging of a homogeneous heated curved metal and nylon test sample. We used finite element modelling to predict the reradiation of concave structures in order to calculate the parameters of an approximating formula for the emissivity dependent on the angle to the normal vector on each element. The differences between experimental and numerical results of the steel test sample are explained using electron microscopy imaging and the validation on different materials. The results suggest that it is possible to determine the errors of thermal imaging testing of complex shapes using a numerical model.

1. Introduction

Most thermographic non-destructive testing research is performed on flat test samples like flat bottom hole plates to improve thermographic post-processing techniques [1]. In general thermographic applications, structural health monitoring inspections are performed on complex shaped structures. With the use of complex geometrical surfaces, there are several parameters which influence the measured radiation, including self-radiation and the angular dependency of the emissivity [2]. Self-radiation is defined as the emittance which is emitted back to the object in the infrared spectral bandwidth. For active thermal inspections a variety of techniques exist which use signal delay measurements and phase images instead of intensity maps to filter the signal from the ambient conditions [1,3,4]. Most applications use IR imaging for passive investigations [3] where the history of preheating is unknown and the influence of emissivity, reflections and ambient conditions are an important aspect of the image evaluation. To predict correct temperature profiles of complex shaped structures it is therefore useful to have a predictive tool to calculate the nominal measured temperature offsets due to directional emissivity of the complex structure versus the real temperatures. Most influences of thermal noise on the measured temperatures, such as the influence of ambient reflections and the influence of sensor noise, could be reduced by the use of multiple view points. Furthermore, the directional emissivity which results in different measured temperature profiles of concave and convex surfaces can only be predicted analytically for simple geometries. The directional emissivity errors are geometry and view point dependent. Nowadays, structures become more and more complex shaped because of the extensive

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implementation of high-end composite materials. Due to the increase in accuracy of thermal cameras over the past ten years, the need arises to eliminate geometry-caused errors in order to be able to measure more precisely and deeper in structures. In the 1970s Kanayama already developed numerical models to describe the directional emittances for rough surfaces [5] theoretically using Fresnel's formula. Furthermore it is well known and broadly discussed that the roughness of a surface influences the emissivity [6]. In the early 1960s a numerical ray tracing technique was developed for V-shaped grooves [7,8] which was further developed by Birkebak and Eckert [9] and Sacadura as shown in [6]. Besides, numerical simulations by finite element (FE) modelling of the directional emissivity on surfaces with random grooves were not considered sufficiently accurate in the 1990s [10]. Recent studies show that with increasing calculation power, the use of finite element modelling to numerically estimate multiple scatterers in three dimensions delivers reliable results [11]. In recent years, major steps were taken towards a better understanding of the directional behaviour of thermal emittance in laboratories [12,6,13–16]. We continue this research by implementing these techniques in realistic structures and designing a technique with which the numerical model can be adapted to the realistic manufacturing conditions.

To estimate the influence of directional emissivity on temperature measurements for quality control, we developed a technique using numerical analysis to model the directional emissivity by updating the emissivity profile from experimental validation data. This paper proposes a methodology to evaluate the experimental directional emissivity with numerical simulation data. Therefore the paper starts with a theoretical overview of the directional dependency of emissivity and the approximation methodologies. Next the experimental measurements of the directional emissivity for a simple concave and convex surface are described. We proceed with the description of the numerical model, followed by a discussion section where we validate the measurements of different samples, and we end with the conclusions.

2. Materials & methods

Within this section we will first deliver some theoretical background of directional emissivity, then we will define the performed experimental measurements and finally we will describe the numerical modelling.

2.1. Theoretical background

The emissivity of a structure is dependent on multiple parameters such as the type of material, the surface roughness, the wavelength range and the angle between the camera and the structure [3,1].

The cosine law of Lambert [1] Eq. (1) shows that the emitted radiation intensity (ΔT_p) has a maximum normal to the face angle and a minimum normal at larger angles δ, as can be seen in Fig. 1:

$$\Delta T_p \sim \epsilon \frac{P\cos(\delta)\,\Delta t}{4\pi R^2 \rho C\,dz} \;(^\circ\mathrm{C}) \qquad (1)$$

where R is the distance between the point source and the object (m), δ the angle between the normal to the surface and the incident ray (rad), P is the heating power (W), ρ the density $(\mathrm{kg/m^3})$, Δt the thermal pulse length (s), dz the depth of penetration of the heating front (m), C the specific heat $(\mathrm{J/kg}\cdot^\circ\mathrm{C})$, and ϵ the directional emissivity. In reality the intensity distribution is far more complex than a Lambert radiator [3]. Most active thermography techniques make use of previously recorded thermograms (ERT) to compensate the radiation distribution for non-planar surfaces [1]. This technique, fully described in [1] has multiple drawbacks:

- Calibration recording before excitation is essential for each part and makes the technique very slow.
- A high-powered source is required of which only a fraction is used.
- The maximum workable workspace and distance are limited.
- Restricted to limited curvature as the $\cos(\delta)$ is unknown.

By using an updated FE model it is possible to predict the thermal response of a complex curved structure by estimating the $\cos(\delta)$ from the geometry data.

By the use of active thermography, the inspected object is heated by a heat source for a short time period. Due to direct emissivity, a certain part of the by itself emitted energy will be reabsorbed again by the structure due to self-radiation. The amount of re-absorbed energy is dependent on the amount of radiation received from the emitting surface, as shown schematically in Fig. 1 by the different sized arrows. In this figure, the blue solid arc represents a curved structure and the gradient arc represents the observed temperature distribution. For the comparison of thermography measurements with theoretical values it is essential to model this viewing angle dependent emissivity. Therefore we need to estimate the angle dependence of the emissivity by defining a custom function. Based on a general Lambertian function dependent of angle δ this function is built for a specific structure by iterative updating of a FE model in order to estimate the directional dependency weights using the Monte Carlo ray tracing routines. The temperature profile of the FE model is compared with the measured temperature profile of the experimental measurements.

2.2. Experimental measurements

To investigate the self-radiation of concave structures, we homogeneously heated a steel and nylon tube section to a temperature above 40 °C using a hot fluid medium on a homogeneous temperature and placing them vertically to deliver an equal convection flux over the full arc in an ambient atmosphere of 22 °C. The tube section is placed in a thermal stable environment with homogeneous ambient reflections and has an elevated homogeneous temperature in advance, in contrast to the absorbing background walls. We expect that the surface temperature at the outer surface of the tube section delivers a horizontal profile with a constant temperature, as self-radiation is impossible at a convex surface. For the inside of the tube we expect a completely different profile as self-radiation influences the measurements of the concave surface. The directional emissivity of the concave surface is shown in Fig. 2. In the concave measurement profile we found two regions of remarkably high temperature measurements at the side of the concave surface. Note that the structure itself is globally 43 °C Celsius but that the outer sides of the concave surface show a higher temperature due to self-reflectivity and self-radiation. The true material temperatures without reflection and self-radiation are measured from the convex side of the tube section. The experimental measurements were performed with a Xenics Gobi640 Gige-E microbolometric camera with 640 × 480 resolution with a NETD of 50 mK and a spectral range of 7–14 μm with negligible external radiation. The camera is placed in front of the tube section under three different angles which are averaged out for each geometrical point of the tube. The tube section is heated to a temperature between 40 and 50 °C which has its maximal spectral emission in the spectral range of the camera. As we know that the temperature of the surface is the same for each point at initial conditions (homogeneously heated), the only possible explanation for this measurement is the view-angle