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Heat Flow Visualization and Thermal Anomaly Detection Using Phase Measuring Deflectometry

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Abstract

This study demonstrates Phase Measuring Deflectometry (PMD) as an optical technique for visualizing heat flow and detecting thermal anomalies in metallic materials. Heat conducted from a thermally loaded sample into an adjacent transparent medium induces spatial refractive index gradients, which distort a projected fringe pattern. These distortions are captured and analysed using PMD, enabling emissivity-independent visualization of the heat flow field. Experimental results on aluminium and structural steel slabs reveal distinct phase signatures linked to thermal conductivity differences. The method offers a compact, non-invasive, and surface-independent alternative to conventional thermography, well-suited for engineering diagnostics and material evaluation.

Keywords

Heat flow visualization, Phase Measuring Deflectometry, Refractive index gradient, Emissivity-independent measurement, Subsurface anomaly detection

1. Introduction

Visualization of heat flow is essential for assessing thermal behaviour and detecting anomalies in a range of applications, including aerospace, automotive systems, and energy devices[1]. Even minor thermal irregularities may indicate internal flaws such as voids or delaminations[2]. Infrared thermography (IRT) is commonly used for surface temperature mapping, but its effectiveness is compromised for metallic surfaces due to high reflectivity and low emissivity, making it challenging to detect subsurface features[3,4].

Digital Holographic Interferometry (DHI) is a state-of-the-art technique for mapping thermal signatures by detecting refractive index variations in surrounding media. However, its practical application is often limited by sensitivity to phase noise, alignment complexity, and restricted dynamic range[5,6]. Phase Measuring Deflectometry (PMD) [7–9], traditionally used for inspecting reflective surfaces, can be adapted to visualize heat-induced refractive index gradients in a transparent dielectric medium in contact with the heated object.

Thermal gradients within a transparent medium results in spatial variations in refractive index, which distort the projected fringe pattern. These distortions are captured and processed using PMD algorithms to reconstruct a two-dimensional phase map correlated with the heat flow distribution. As this method does not depend on surface emissivity, it remains effective for coated or reflective materials. Unlike infrared thermography, which requires accurate knowledge of surface emissivity and may struggle with highly reflective materials, PMD is unaffected by surface properties and remains effective on coated or metallic samples. Moreover, PMD produces stable, high-contrast reconstructions without the environmental and alignment sensitivity commonly associated with interferometric techniques, making it a more practical choice for real-world thermal diagnostics.

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In this work, the technique is demonstrated by comparing heat flow behaviour in aluminium and structural steel slabs placed side by side under identical thermal loading conditions.

2. Theory

PMD operates by projecting a structured fringe pattern through or onto a transparent dielectric medium and capturing its deformation using a camera[8–10]. When a thermally stressed metallic sample transfers heat into the adjacent medium, it creates temperature gradients that induce spatial variations in the refractive index via the thermo-optic effect[5,6,11,12]. These refractive index gradients alter the direction of the light rays, leading to phase distortions in the observed fringe pattern. As illustrated in Fig. 1, the rays bend toward regions of higher refractive index, with the degree of bending reflecting the magnitude and direction of the thermal gradient[13,14].

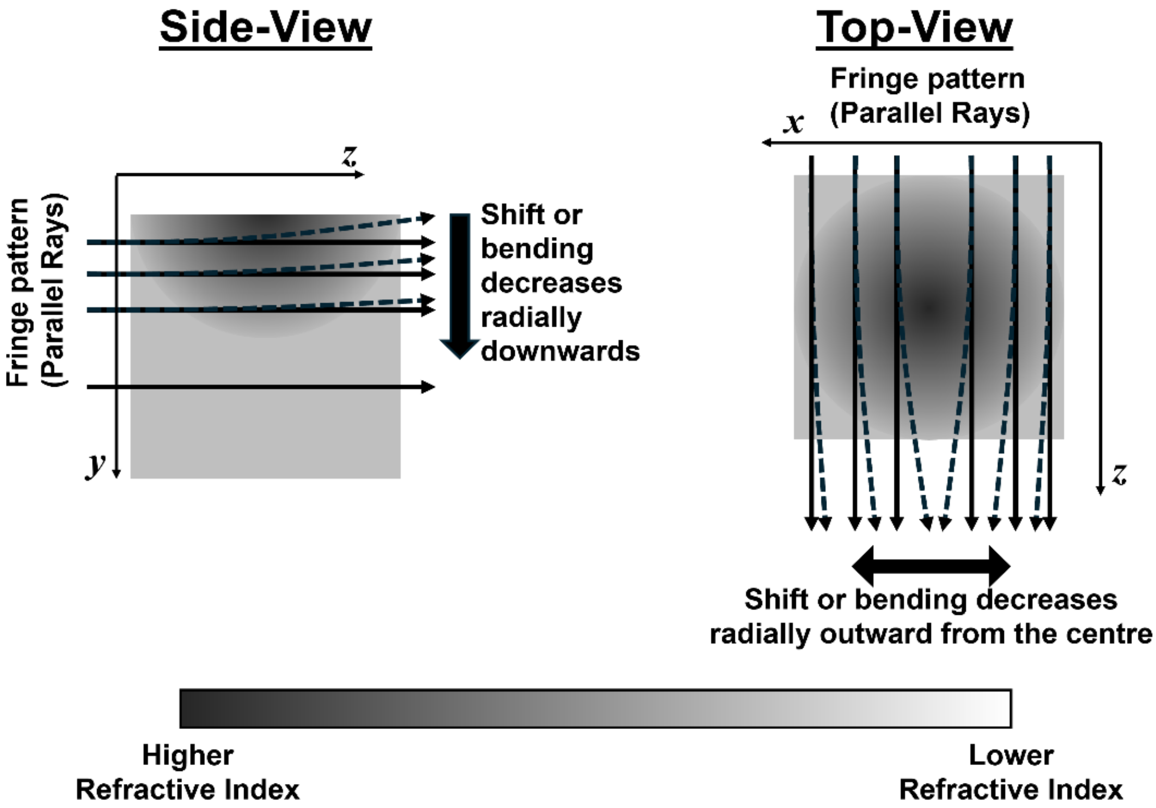


Fig. 1: Bending of light rays due to refractive index gradients

The recorded fringe images are then processed to extract spatial phase distributions that represent integrated optical path differences. The numerically reconstructed gradient phase (ϕ) from the recorded fringe pattern (which is proportional to the angle of deflection) can be written as

$$\phi = \frac{2\pi d}{p}\mu t\frac{\partial T}{\partial y} \tag{1}$$

where d is the distance between the fringe pattern and the phase object, μ is the thermo-optic coefficient, t is the thickness of the phase object, μ is the thermo-optic coefficient ($\frac{dn}{dT}$), and p is the fringe width. Assuming refractive index variations arise primarily due to temperature, the phase information can be correlated with the underlying thermal field using the thermo-optic coefficient.

These phase maps serve as indirect but effective visualizations of heat flow, offering an emissivity-independent means of detecting material inhomogeneities and thermal anomalies without requiring direct surface temperature measurements.

3. Experimental Setup

A PMD based system as shown in Fig. 2 was used to record temperature-induced optical phase distortions in a transparent dielectric medium (distilled water) placed under the metallic samples. A digital sinusoidal fringe pattern inclined at 45° to the horizontal (displayed on a high resolution display: 1080 × 1920 pixels, 403 pixels per inch, 800 nits) was imaged through the medium, and its deformation due to refractive index gradients was captured using a CCD camera (8-bit, 4.65 µm pixel pitch, 768 × 1024 pixels). Thus, the optical setup consisted of a programmable display unit, imaging chamber, and recording system as shown in the Fig. 2.

Aluminium and structural steel (SS) slabs of identical dimensions were placed adjacent to each other and uniformly heated from above. A thin aluminium foil (200 µm) was placed between the samples and the imaging chamber to serve as a thermal interface while providing an optical occlusion.

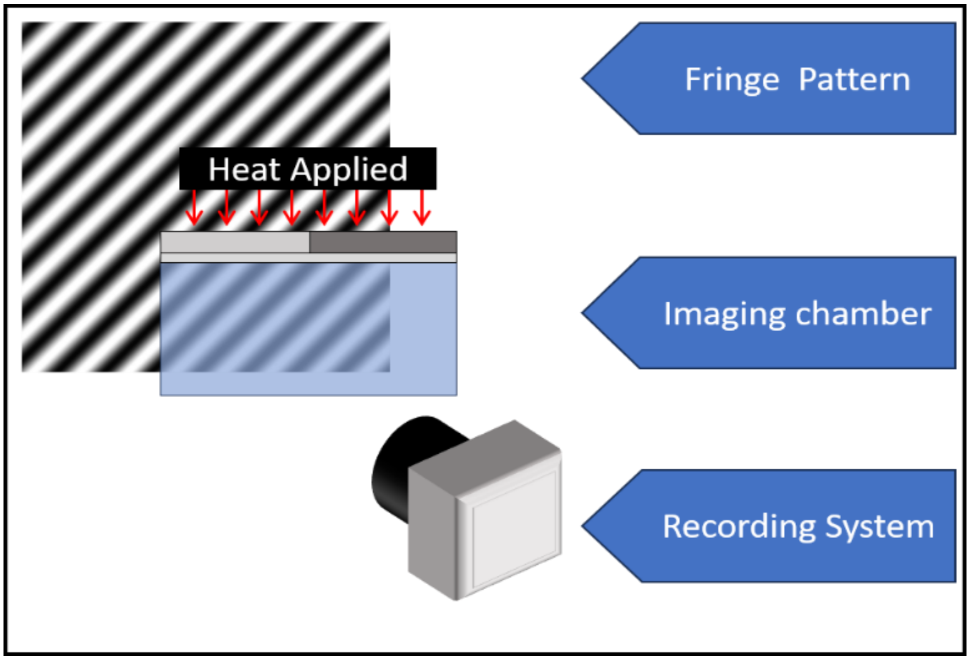


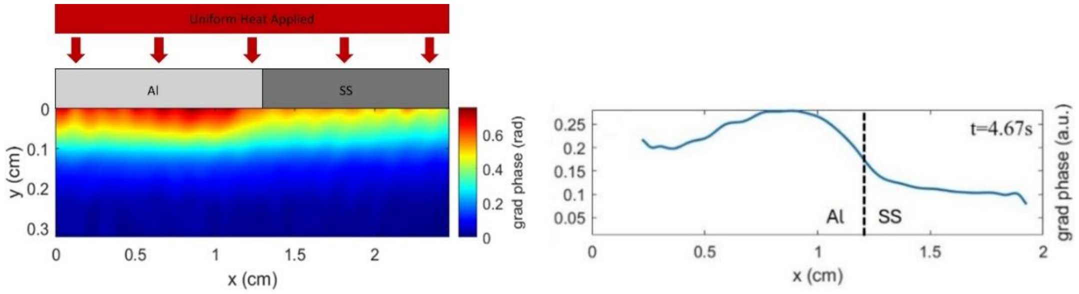
Fig. 2: Schematic of the experimental setup

4. Results and Discussion

The experimental phase map acquired for aluminium and structural steel slabs under identical thermal excitation demonstrates the utility of Phase Measuring Deflectometry (PMD) for visualizing heat flow and identifying material differences. The phase distribution under the aluminium slab exhibits greater magnitude and wider spatial extent compared to that under the structural steel slab, consistent with aluminium's higher thermal conductivity.

These differences are optically resolved via refractive index gradients in the dielectric medium as shown in Fig.3, confirming the method’s sensitivity to intrinsic material properties. The fringe-based phase reconstruction provided stable and high-contrast output without requiring stringent surface emissivity conditions, a common limitation in infrared thermography.

Moreover, the use of a simple dielectric layer and standard imaging optics allows for a compact, emissivity-independent, and repeatable experimental platform suitable for comparative material studies. PMD proves especially advantageous for reflective or coated surfaces where conventional thermal imaging is unreliable.



(a) (b)

Fig. 3: Phase map visualizing heat flow through aluminium (left) and structural steel slabs at 4.67 s after thermal excitation

5. Conclusion and Future Scope

The results demonstrate the feasibility of using Phase Measuring Deflectometry (PMD) for optical visualization of heat flow and detection of thermal anomalies in metallic materials. The clear contrast in phase distribution between aluminium and structural steel reflects the system's sensitivity to differences in thermal conductivity and validates the technique's ability to distinguish dissimilar materials under uniform heating conditions.

Unlike infrared thermography, which depends on surface emissivity, the presented approach is based on refractive index modulation in a transparent medium, enabling reliable diagnostics even on reflective or coated surfaces. The spatial resolution and contrast achieved in the reconstructed phase maps highlight the capability of PMD to resolve subtle thermal gradients through indirect, non-invasive optical probing.

The method is compact, scalable, and cost-effective, requiring minimal alignment compared to interferometric systems. Its adaptability to different dielectric media and material types makes it suitable for a range of applications in thermal diagnostics, material evaluation, and non-destructive testing.

Future work may focus on quantitative phase-to-temperature calibration, dynamic analysis of transient heat events, and integration with data-driven techniques for automated defect detection.

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