Article

Estimate of the properties of thermal coatings by means of pseudo-noise active thermography

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Abstract: The application of thermal barrier coatings (TBCs) for protecting mechanical components is widespread, particularly in high-temperature environments such as gas turbines and aero-engines. Ensuring the integrity of these coatings throughout their service life is essential, as their degradation can lead to delamination, ultimately compromising the underlying component. It has been demonstrated that monitoring the thermal diffusivity value along time allows the monitoring of degradation of the coatings. Common thermographic techniques like pulsed and lock-in thermography have been used so far. However, to enhance both the signal-to-noise ratio (SNR) and the accuracy of thermal property measurements, new active thermography techniques have been developed. These methods rely on optimized excitation schemes combined with advanced signal processing strategies. In this work, we first introduce the pulse-compression thermography approach, which employs pseudo-noise modulated excitation to monitor and estimate the thermal diffusivity of the coating layers.

Keywords: NDE; Thermal Barrier Coatings; Pulse Compression Thermography

1. Introduction

Ceramic thermal barrier coatings protect parts — especially those facing very hot combustion gases in gas turbines — by keeping them from getting too hot and corroded. A TBC has two main layers on the metal part: a bond coat made of metal alloy and a top coat made of ceramic. These layers are applied by methods like EB-PVD or air plasma spray. The ceramic layer (often 7 % yttria-stabilized zirconia) blocks heat and handles temperature changes, while the bond coat (such as MCrAlY alloys) helps the ceramic stick, matches how the metal expands, and stops oxidation. It's important to check how the coating's ability to insulate changes over time [1]. Instead of steady-state tests, people often use quick, transient tests to measure thermal diffusivity α, like photothermal methods. The advancement of thermographic techniques has enabled in-situ evaluation of layered materials such as thermal barrier coatings. Among these, Thermal Wave Interferometry (TWI) stands out for its high accuracy [2,3]. This method introduces modulated thermal waves into the coating and analyzes their reflections at material interfaces. By precisely measuring phase shifts and changes in the surface temperature response, TWI provides detailed information about the thermal properties of the coating layer. However, these traditional methods may suffer from limitations in terms of signal-to-noise ratio (SNR), resolution, or sensitivity. To address these challenges, advanced active thermography techniques have been introduced, leveraging optimized excitation schemes and signal processing strategies to enhance data quality and parameter extraction. In this work, we

Published:

Citation: Zito, R.; Ferrarini, G.; Bison, P.; Ricci, M.; Laureti, S. Estimate of the properties of thermal coatings by means of pseudo-noise active thermography. *Proceedings* **2025**, *1*, 0. https://doi.org/

propose the use of a technique recently defined by the authors, aka pseudo noise pulse-compression thermography (PN-PuCT) to replace a square excitation whose duration can be tuned to cope with the characteristics of the sample under test [4]. We demonstrate that LED-based PuCT can achieve diffusivity measurements comparable to standard methods.

2. Materials and Methods

2.1. PN - Pulse Compression Thermography

PN-PuCT replaces a single long heat pulse with a longer, coded excitation whose amplitude is modulated by a pseudo-noise (PN) sequence $x(t)$ of length N_{bit}. After removing the slowly varying 'DC' component from each pixel's temperature time-trend (for example, by polynomial fitting to isolate the alternating 'AC' response), the recorded signal $y(t)$ is cyclically convolved with a matched filter $\psi(t)$, chosen as the time-reversed version of $x(t)$. The output is exactly the response to a virtual rectangular pulse of length T_{bit}, with no sidelobes. Figure 1 summarizes the PN-PuCT procedure.

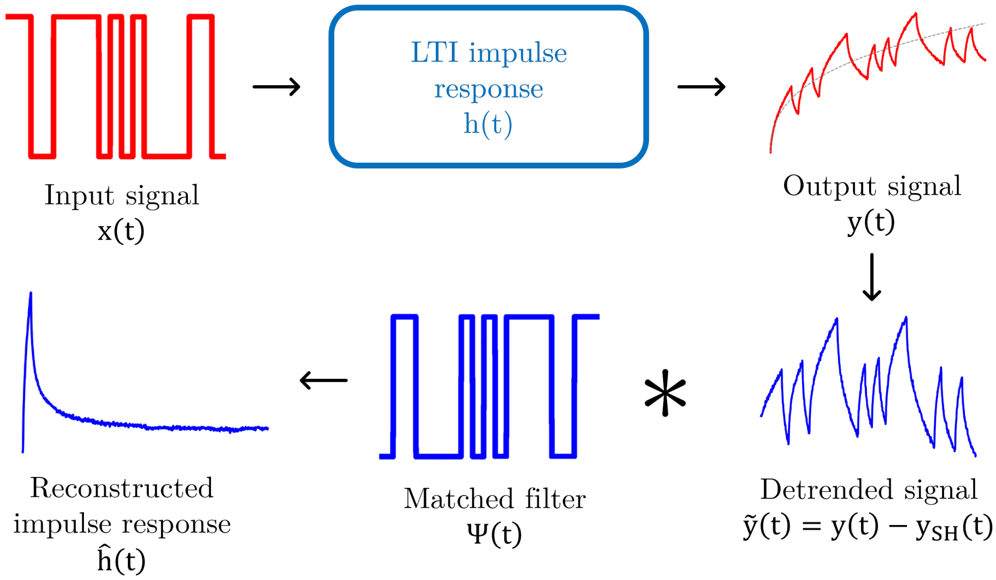

Figure 1. PuCT procedure with pseudo-noise excitation.

Thus, by selecting appropriate PN sequences (e.g., maximum-length or Legendre sequences) and bit durations, PN-PuCT delivers high-contrast, sidelobe-free thermograms as if a high-power pulse had been used, but with the energy and flexibility advantages of a coded, lower-power excitation. The scope of this article extends beyond the application of PN-PuCT. For a more detailed introduction to the fundamentals of this technique, the reader is referred to [4].

2.2. Heat Model

In the context of TBCs, the bilayer heat conduction model plays a critical role in accurately interpreting surface temperature responses during active thermography. The ceramic layer usually ranges from tens to hundreds of micrometers in thickness, while the underlying substrate is often treated as semi-infinite due to its larger thickness. This sharp contrast in geometrical and thermal properties leads to significant wave reflection and transmission effects at the interface, which must be accounted for in any thermal analysis. When the surface of such a bilayer system is heated by a thermal pulse (or equivalent coded excitation), the temperature response must be modeled using the composite bilayer solution. Equation 1 represents a specific case of a more general analytical solution for transient heat conduction in a bilayer system, consisting of a finite-thickness surface layer deposited on a semi-infinite substrate with different thermophysical properties. Under the assumptions of adiabatic boundaries and negligible heat exchange with the environment, the surface temperature response to a Dirac-type heat pulse applied at the front face is described by the following solution [5]:

$$T(t) - T_0 = T_\infty \frac{L}{\sqrt{\pi \alpha t}} \left[1 + 2 \sum_{n=0}^{\infty} \Gamma^n e^{-\frac{n^2 L^2}{\alpha t}} \right] \quad (1)$$

with $\Gamma = \frac{e_c - e_s}{e_c + e_s}$ the reflection coefficient, ranging from -1 to +1 and accounting for the mismatch between the effusivity of the coating layer e_c and that of the substrate e_s, α and L the thermal diffusivity and the thickness of the coating layer respectively.

3. Results

Thermal diffusivity was extracted from measurements performed on two TBC samples, with a nominal thickness of 130 μm. Each sample was subjected to the same PN - PuCT LED excitation. To minimize any thermal or mechanical impact on the coating, heat excitation was provided by four 100 W high-power LED chips rather than conventional flash lamps or lasers. A PC/DSP unit controlled the function generator, which produced the pseudo-noise modulation signal. This PN waveform drove a programmable power supply feeding the LED array, and simultaneously issued a hardware trigger to synchronize the FLIR A6751 infrared camera with the excitation. Thermograms were recorded throughout the coded heating sequence, with the camera positioned approximately 150 mm from the sample surface. The impulse response reconstructed using the PN-PuCT technique is equivalent to the thermal response that would be obtained from a single, ideal thermal pulse of 0.1 seconds in duration. The results of fitting and estimated diffusivity are reported in Figure 2.

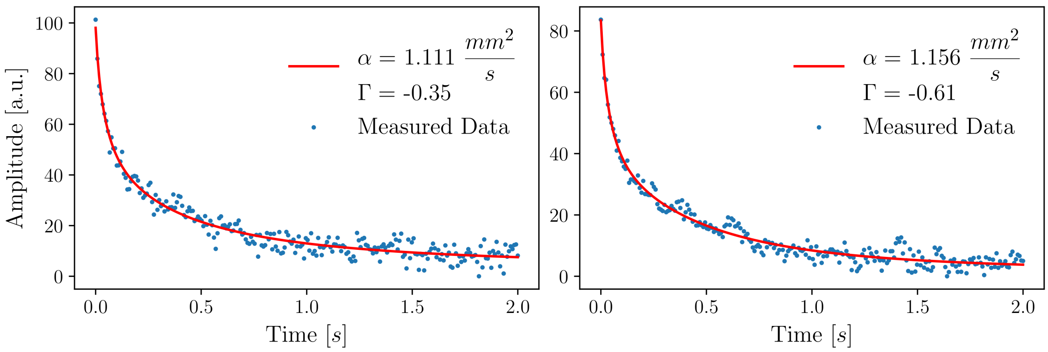

Figure 2. Comparison between experimental surface temperature data (dots) and fitted model response (solid line) for the two sample. The fitting was performed using a two-layer heat conduction model, allowing accurate estimation of the coating's thermal diffusivity.

For the sake of clarity, the experimental results obtained using PN-PuCT are also summarized in Table 1.

Table 1. Estimated values of thermal diffusivity α and reflection coefficient Γ

Sample	Γ	α $[m^2 s^{-1}]$
Sample #1	-0.35	1.111×10^{-6}
Sample #2	-0.61	1.156×10^{-6}

These outcomes demonstrate the feasibility of estimating the thermal diffusivity of thermal barrier coatings with reasonable accuracy. Across multiple samples, the reconstructed impulse responses allowed diffusivity values to be extracted that were in good agreement with expected values [6].

Further improvements in excitation uniformity, calibration, and signal processing are expected to enhance precision in future applications.

Author Contributions: Conceptualization, S.L.,P.B. and M.R.; methodology, S.L.,R.Z. G.F. and M.R.; software, R.Z. and S.L.; validation, R.Z., G.F. and S.L.; investigation, S.L. and G.F.; data curation, R.Z.; writing—original draft preparation, R.Z., G.F.; writing—review and editing, R.Z., G.F. and S.L.; visualization, R.Z. and S.L.; supervision, M.R. and P.B. All authors have read and agreed to the published version of the manuscript.

Funding: This work was partially funded by the Next Generation EU-Italian NRRP, Mission 4, Component 2, Investment 1.5, call for the creation and strengthening of 'Innovation Ecosystems', building 'Territorial R&D Leaders' (Directorial Decree n. 2021 / 3277) - project Tech4You - Technologies for climate change adaptation and quality of life improvement, n. ECS0000009. This work reflects only the authors' views and opinions, neither the Ministry for University and Research nor the European Commission can be considered responsible for them.

Conflicts of Interest: The authors declare no conflicts of interest.

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