Multi-Gaussian modelling of laser speckle fields from carbon fibre reinforced plastic

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DOI
10.1117/12.3066346

Publication date
2025

Document Version
Final published version

Published in
Modeling Aspects in Optical Metrology X

Multi-Gaussian modelling of laser speckle fields from Carbon Fibre Reinforced Plastic

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ABSTRACT

Carbon Fibre Reinforced Plastic (CFRP) exhibits complex optical behaviour due to its anisotropy and highly scattering surface. These optical characteristics pose significant challenges for the automated laser-based inspection systems used in CFRP manufacturing, as they lead to variations in light interaction with the material, affecting the accuracy and reliability of inspections. To investigate this complex optical behaviour, an inverse optical model based on the Multi-Gaussian method has been developed. Laser speckle patterns from the CFRP surface are decomposed into multiple Gaussian components to model the material's optical properties. A greedy optimisation algorithm is employed to estimate the optimal coefficients for the Gaussian sets, which are further refined by introducing negative amplitude Gaussian components. These enhancements improve the optimisation, resulting in a better correlation between the Multi-Gaussian model and actual laser speckle measurements.

Keywords: CFRP, Multi Gaussian, Inverse Modelling, Greedy Algorithm.

1. INTRODUCTION

Carbon fibre-reinforced Plastic (CFRP) is widely adopted in aerospace structures due to its high strength-to-weight ratio and resistance to fatigue and corrosion. Their application in critical structures demands reliable manufacturing and inspection methods. Inline, non-contact inspection has gained prominence for detecting defects during production, improving manufacturing efficiency by up to 25%.[1] Laser-based techniques—such as thermography, laser line scanning, and machine vision—have shown promise for defect detection in composites.[2] However, their performance is strongly influenced by the optical behaviour of CFRPs, which is complex due to their anisotropic and heterogeneous structure.[3] This causes variability in reflected laser light, posing a significant challenge for consistent, automated inspection[4].[5] Understanding this light–material interaction is essential to develop optimised inspection systems and accurate defect detection methods.

In this paper, we describe the methodology used for modelling reflected light fields using multiple Gaussian elements. A greedy optimisation algorithm is used to determine the minimal set of Gaussians that could accurately represent the measured speckle pattern.

2. MULTI-GAUSSIAN MODELLING OF SPECKLE FIELDS

Speckle patterns are apparently random interference phenomena resulting from coherent wave interaction with a rough surface.[6] The speckle field, U, with intensity $I(x, y)$ and phase, $\phi(x, y)$, is to be modelled as the sum of multiple Gaussian fields as;

$$U = I(x, y).e^{i\phi(x,y)} \approx \sum_{i}^{N} G_i(x, y). \tag{1}$$

Where $G_i(x, y)$ is the i^{th} Gaussian profile, and N is the number of Gaussians required to optimise.

$$G(x, y) = A \cdot \exp\left(-\left[\frac{(x - m_x)^2}{2\sigma_x^2} + \frac{(y - m_y)^2}{2\sigma_y^2}\right]\right) .e^{\phi_i(x,y)} \tag{2}$$

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Modeling Aspects in Optical Metrology X, edited by Bernd Bodermann, Karsten Frenner,
Proc. of SPIE Vol. 13568, 135680I · 2025 Published by SPIE
0277-786X · doi: 10.1117/12.3066346

Where A is the amplitude of the Gaussian, m_x and m_y are the position of Gaussian along the x and y directions, respectively, σ_x and σ_y are the widths of Gaussian along the x and y directions, respectively, and $\phi(x, y)$ is the phase of the Gaussian.

Each Gaussian profile is thus described by six parameters, resulting in a total of $6\times N$ parameters for a complete model. This modelling approach aims to determine an optimal set of these parameters such that the constructed field closely approximates the original speckle pattern, using as few Gaussians as possible. Among various algorithmic approaches, a greedy optimisation method is adopted in this study to estimate the model parameters.

2.1 Greedy Algorithm Optimisation for Modelling Speckle Intensity

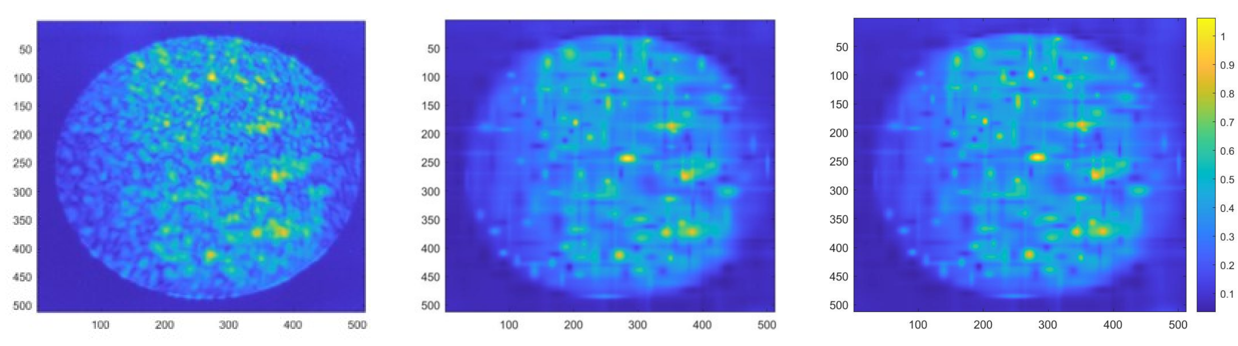
The greedy algorithm selects the best possible solution for a given problem by reducing the cost function at the given time.[7] In this context, it identifies the optimal set of six Gaussian parameters closely matching the speckle intensity at each step. The algorithm has been implemented in MATLAB. The algorithm fits one Gaussian at a time using nonlinear least squares, subtracts it from the speckle data, and proceeds to fit the next component to the residual. This process continues until the residual is sufficiently reduced. The objective function $E(\theta)$ is defined as

$$E(\theta_i) = \sum_{x,y} \left[I(x, y) - G_i(x, y; \theta_i) \right]^2 \tag{3}$$

Where $\theta = \{A, m_x, m_y, \sigma_x, \sigma_y\}$ are the five parameters of the Gaussian profile. At each iteration, the mean squared error (MSE) and correlation coefficient (CC) between the speckle amplitude and the Gaussian approximation are computed to assess performance. To address algorithmic saturation at higher iteration levels, negative amplitude Gaussians are also included. Although not physically intuitive, they allow phase-reversed components that improve approximation by cancelling additive effects in specific regions. As mentioned earlier, another objective of this optimisation is to keep the number of Gaussian elements as small as possible. Since not all components contribute equally, a 'best of the best' filtering step retains only those Gaussians that provide a significant reduction in the MSE.

2.1.1 Results

The input speckle intensity was recorded from a CFRP sample and preprocessed through cropping and normalisation for consistency. Incorporating both positive and negative amplitude Gaussians was found to improve the correlation with the measured speckle pattern. The greedy optimisation algorithm, incorporating negative amplitude Gaussians and a filtering step to retain only the most significant components, was applied to reconstruct the speckle pattern. Figure 1 shows the intensity of experimentally recorded speckle from the CFRP sample and the respective reconstructed Gaussian model.



(a) (b) (c)

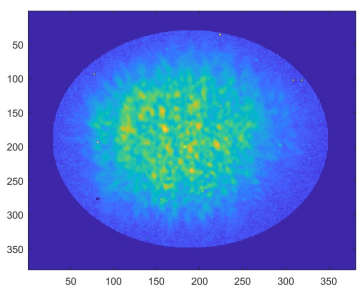
Figure 1: Recorded speckle intensity (fig. a). The respective reconstructed Gaussian intensities using the greedy algorithm method in 1000 steps, with MSE of 0.002 and CC of 0.9835 (fig. b). The best reconstructed Gaussian set selected with 384 Gaussian elements with MSE of 0.0030 and CC of 0.9827 (fig. c).

2.2 Greedy Algorithm optimisation for Modelling Speckle Fields

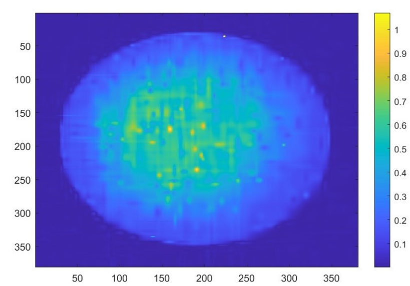
Optical speckle fields are to be characterised by phase and intensity, as described in 1. To extend the previous real-valued intensity modelling, the sixth parameter, phase, is included to characterise the full complex speckle field. The greedy optimisation algorithm is accordingly adapted to minimise a complex-valued objective function. The adapted algorithm employs MATLAB's modified nonlinear least squares fitting routine to fit a 2D complex Gaussian to the residual field at each step. The correlation is evaluated using the magnitude of the mean squared error and a complex correlation function. Also, the objective function has been split into real and imaginary parts of the complex difference between the model and the speckle field. Due to phase ambiguity, only Gaussian components that improve the fit compared to the previous iteration are retained. The preliminary results obtained from the extended greedy optimisation for modelling speckle fields are shown in section 2.2.1

2.2.1 Results

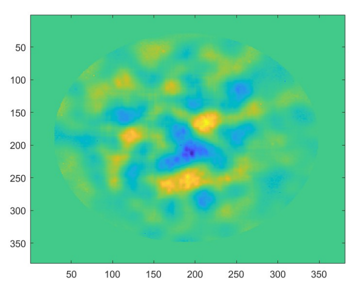
The speckle fields are generated by experimentally measuring speckle intensity using a camera and combining it with sample phase information for preliminary analysis.



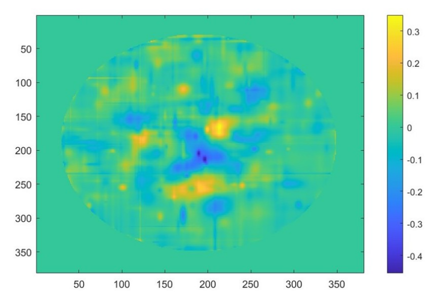
(a) $|U|$



(b) $|G|$



(c) $arg(U)$



(d) $arg(G)$

Figure 2: The figure shows measured speckle intensity (fig. a) and simulated phase (fig. c), reconstructed Gaussian field with Gaussian model intensity (fig. b) and Gaussian model phase (fig. d). The MSE value calculated between the absolute value of the speckle field and the Gaussian model is 0.0009.

3. DISCUSSION AND CONCLUSION

A multi-Gaussian modelling approach was developed for inverse simulation of light interaction with anisotropic CFRP surfaces. Using a greedy algorithm, speckle intensity and complex fields were reconstructed with high correlation to experimental data. The number of Gaussian components required was found to depend on how much the speckle pattern deviates from a standard Gaussian profile.

Incorporating negative amplitude Gaussians improved reconstruction accuracy by compensating for additive effects. The results provide a basis for further analysis, where selected Gaussian components will be backpropagated to the material surface. Combined with laser source characterisation, it is assumed to give a correlation between the reconstructed speckle fields and the surface properties of the carbon composite material.

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ACKNOWLEDGMENTS

This work is funded by the Dutch government project 'Luchtvaart in Transitie'under its sub-project 'Developing Lightweight Composites and Structures'.

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