euspen's 25th International Conference & Exhibition, Zaragoza, ES, June 2025
www.euspen.eu

Evaluating surface reconstruction methods for coherence scanning interferometry

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Abstract

Optical interferometry, particularly coherence scanning interferometry (CSI), is widely used in precision manufacturing to measure surface topography with sub-nanometre repeatability. In this approach, surface topography is determined by analysing a series of images captured at different scan positions as the surface is scanned. A surface reconstruction algorithm then processes the signal data at each pixel along the optical axis, to calculate the surface height at each point. Consequently, the accuracy of these height measurements is significantly influenced by the effectiveness of the reconstruction method used. Given the importance of reliable and repeatable surface measurements for quality control, design optimisation and product validation, it is necessary to employ reconstruction methods that provide accurate results under real-world conditions. In this study, we simulate CSI signal data for a quasi-random profile, while applying different noise levels. The performance of example implementations of widely used reconstruction methods—the Hilbert transform, frequency domain analysis and continuous wavelet transform—is evaluated, considering both envelope and phase information obtained from the interference fringes. The findings highlight the importance of choosing suitable reconstruction methods to obtain accurate and reliable surface height data in high-noise environments.

Coherence scanning interferometry, signal modelling, surface reconstruction, Fourier analysis.

1. Introduction

Accurate measurement of surface topography is essential in precision engineering to ensure product performance and quality [1]. Coherence scanning interferometry (CSI) is a widely used non-contact technique in fields such as advanced manufacturing, electronics and biomedical engineering, capable of measuring complex surface geometries with sub-nanometre repeatability [2].

CSI captures a stack of images along the vertical axis as the object surface is scanned [2]. A crucial step is converting the recorded interference images into surface height data using a reconstruction method. However, extracting accurate height information from interference fringes is challenging due to noise, highlighting the need for robust reconstruction methods to ensure reliable surface measurement [3].

Surface reconstruction methods are often categorised into three approaches: envelope-based approaches [4], which detect the envelope peak position of the interference signal to evaluate surface height, phase-based algorithms [5], which rely on phase demodulation of the fringes, and correlation-based methods [6], which use signal matching techniques to locate interference maxima. The continuous wavelet transform (CWT) [7], frequency domain analysis (FDA) [8] and Hilbert transform (HT) [9] are the most common reconstruction techniques and employ envelope and/or phase-based approaches for the evaluation of surface height. Despite the importance of analysing the performance of different reconstruction methods under varying signal-to-noise ratio (SNR) levels, comprehensive studies in the literature remain limited [10-13]. Moreover, existing research primarily focuses on the accuracy of the reconstruction of step heights [10, 11], whereas the effects of noise become more significant when reconstructing complex surface geometries with continuously varying curvature and slope angle.

In this study, the performance of various reconstruction methods based on envelope peak position detection and analysis of the phase of the fringes, including CWT, FDA and HT, is investigated at different SNR levels ranging from 10 dB to 50 dB. The results are compared according to the specific implementations of the methods. The CSI signal with added noise is simulated for a quasi-random surface, and the mean absolute error (MAE) of the reconstructed profile is calculated for each method.

2. CSI signal modelling and reconstruction methods

A quasi-random input profile is simulated with a known root-mean-square height, autocorrelation length and the total length. Using the object's height h, the CSI signal at each (x, y) position along the optical axis can be expressed as [14]

$$I\,(z) = I_{ref}(z) + I_{obj}(z) + 2\sqrt{I_{ref}(z) I_{obj}(z)}\; exp\left\{-\left[\frac{(z-h)\pi\Delta\lambda}{\ln(2)\lambda_0^2}\right]^2\right\}\cos\left[\frac{4\pi(z-h)\cos(A_N)}{\lambda_0}+\varphi\right], \quad (1)$$

where I_{ref} and I_{obj} represent the intensities corresponding to the reference and object optical paths, respectively, λ_0 and $\Delta\lambda$ denotes the mean wavelength and the full width at half the maximum bandwidth (FWHM) of the light source, A_N is the numerical aperture of the objective lens, and φ is the constant initial phase relying on the optical system. Once the signal is simulated, intensity noise is added to make it representative of real-world conditions. The noise level of a signal is commonly described using the SNR, defined as the ratio of the signal power to the noise power [15].

FDA applies a Fourier transform to CSI interferograms to extract phase data, from which surface heights are determined. It can be implemented based on two approaches: FDA-Norm, which estimates height from the slope of the phase of the fringes versus spatial frequency curve, and FDA-High, which refines the estimate by extracting phase at the spatial frequency where the modulus of the Fourier transform is maximum. It should be noted that in the implementation of the FDA algorithm, as with other methods, all frames of the dataset are considered for each pixel. This differs from the published version of the FDA algorithm, where a 64-frame data trace containing only high-contrast data is used for each pixel [8, 16]. The HT-ENV method calculates the envelope using the Hilbert transform, identifying the envelope peak, which represents surface height, through Gaussian fitting. The HT-Phase method uses phase information from interference fringes. Unlike the FDA method, the HT-Phase approach extracts phase information from the interference fringes by generating an analytic CSI signal in the space domain using HT. The CWT method, using a Morlet wavelet [7], provides a localised space-frequency representation of the signal. Using a CWT approach, the correlation coefficient between the signal and wavelet is calculated in the spatial frequency domain, where the peak position of the envelope is determined by fitting a Gaussian function to the sum of the modulus of the correlation coefficient function along the spatial frequency axis.

3. Results and discussion

A quasi-random input profile is simulated with a root-mean-square height of 0.15 µm^2, a correlation length of 1 µm, and a total length of 36 µm. The CSI signal is generated using Eq. (1), with lateral and vertical sampling distances set as 0.17 µm and 0.075 µm, respectively. The mean wavelength and FWHM of the light source are 0.57 µm and 0.08 µm, respectively, and the numerical aperture of the objective lens is 0.55. Fig. 1 (a) shows the quasi-random input profile, and (b) presents the height difference between the input profile and the height obtained by our implementations of the CWT-ENV, FDA-Norm, FDA-High, HT-ENV and HT-Phase reconstruction methods at an SNR level of 20 dB. In Fig. 1, it is shown that the reconstructed profiles obtained by our implementation of the HT-Phase and FDA-Norm methods show the lowest and highest deviation from the input profile, respectively, at an SNR level of 20 dB. The HT-ENV and CWT-ENV methods, which are both based on the detection of peak envelope position, exhibit the second lowest height error among the methods. FDA-High exhibits height error due to incorrect fringe order determination caused by the low SNR, emphasising its sensitivity to noise.

Fig. 2 shows the MAE of various reconstruction methods for the quasi-random profile across SNR levels ranging from 10 dB to 50 dB. The MAE decreases as the SNR increases for all reconstruction methods. At an SNR of 10 dB, the HT-ENV method achieves the lowest MAE, highlighting its robustness to low SNR levels. However, phase-based methods demonstrate the lowest MAE at SNR levels of 30 dB and above. FDA-Norm presents the highest MAE across all SNR levels, indicating that this method is suitable only for initial height estimation. The envelope-based methods, CWT-ENV and HT-ENV, exhibit nearly identical MAE values between 20 dB and 40 dB.

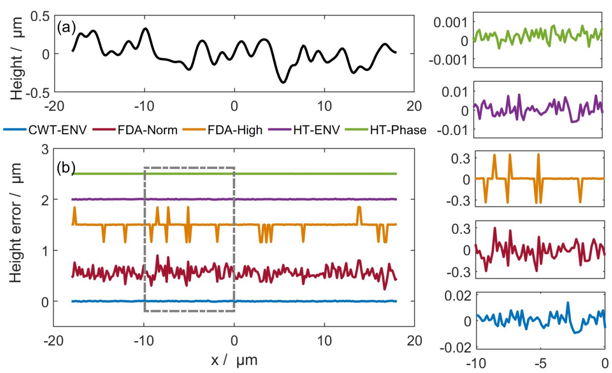

Figure 1. (a) Quasi-random input profile, and (b) the height error obtained by various reconstruction methods at an SNR of 20 dB. The boxes on the right magnify the height error corresponding to different reconstruction methods (note the scale of the vertical axis).

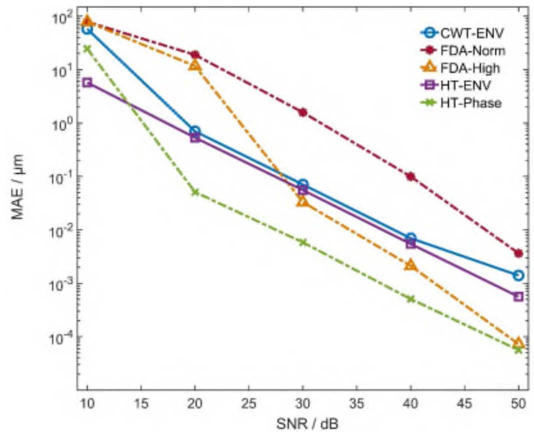

Figure 2. MAE of the CWT, FDA and HT methods versus SNR levels.

4. Conclusion

CSI is a widely used technique in precision manufacturing; however, its performance relies on the reconstruction method used to extract surface height data from interference fringes. This study presents a performance analysis of five reconstruction methods, including envelope-based approaches, such as CWT-ENV and HT-ENV, and phase-based approaches, such as FDA-Norm, FDA-High and HT-Phase. The results demonstrate that the phase-based methods, HT-Phase and FDA-High, achieve superior accuracy at SNR levels of 30 dB and above, while FDA-Norm consistently exhibits the highest error, limiting its use to initial height estimation. The envelope-based methods, CWT-ENV and HT-ENV, show similar error levels over a moderate range of SNR levels, whereas HT-ENV shows high robustness to noise at low SNR. These findings highlight the importance of choosing appropriate reconstruction methods for accurate surface height data. However, a single profile may not fully represent performance of various reconstruction methods, making it essential to analyse various profiles in future studies to determine the best method for each application.

Acknowledgments

This work was supported by the European Union [ERC, AI-SURF, 101054454, UKRI EP/X031675/1]. The authors acknowledge Dr Peter de Groot and Prof. Han Haitjema for fruitful technical discussions.

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