Fringe analysis methods for noninvasive metrology and precision engineering

Pramod Rastogi and Rajshekhar Gannavarpu

Techniques for reliable estimation of phase and its derivatives enable optical metrology with high estimation accuracy, good computational efficiency, and robustness against noise.

In recent decades, optical techniques such as electronic speckle pattern interferometry, holographic interferometry, and fringe projection have emerged as the prominent tools for noncontact measurements. These methods have enormous utility in diverse areas, ranging from biology to materials science, and cover a variety of applications. Examples include material inspection and characterization, nondestructive testing and evaluation, flow visualization, surface profilometry, and biomechanics. In all of these processes, information about the measured physical quantity, such as deformation, strain, profile, and refractive index, is stored in the phase or associated derivatives of an interference fringe pattern (produced where waves overlap). Hence, reliable estimation of phase and its derivatives, commonly referred to as fringe analysis, becomes a primary requirement for these optical techniques.

Over the years, we have developed several fringe analysis methods, focusing on the challenging objectives of high estimation accuracy, good computational efficiency, non-requirement of filtering and unwrapping operations (techniques commonly applied to obtain a continuous phase distribution), single-shot measurement capability, and robustness against noise. The basic idea has been to apply advanced signal processing techniques to address these issues. Accordingly, we have proposed two approaches based on parametric and nonparametric signal analysis. The parametric method relies on local polynomial phase modeling, where we approximate the phase as a polynomial within a finite segment or block. Thus, we transform phase estimation into a parameter estimation problem, with the polynomial coefficients of the different segments being the respective parameters. This formulation enables the application of robust techniques for phase retrieval, such as high-order instantaneous moments, subspace method, phase-differencing operator, and state-space approach. Our method is applicable to a fringe pattern: see Figure 1(A). Figure 1(B) and (C) shows the estimated phase and corresponding error, highlighting the accuracy of our approach.

In addition to phase, other quantities of significant interest are phase derivatives. These provide important information for experimental mechanics and precision engineering regarding strain and curvature distribution, surface defects, and fracture mechanisms of a deformed object. To estimate the phase derivatives, we proposed a nonparametric approach based on space-frequency analysis. We localized the signal using a window function, and formulated a space-frequency distribution.

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We then ascertained information about the phase derivatives by examining the spectral properties of the windowed distribution. Using this approach we established several phase derivative estimation techniques based on pseudo-Wigner-Ville distribution,\cite{6-8} complex-lag distribution,\cite{9} and adaptive windowing methods.\cite{10,11} Figure 2(A) shows the fringe pattern. We extracted phase derivatives with respect to the horizontal and vertical dimensions—see Figure 2(B) and (C)—and also identified the corresponding estimation errors: see Figure 2(D) and (E). Evidently, the proposed approach allows direct estimation of the phase derivatives without numerical differentiation and filtering operations.

Another focus of our research is the development of multicomponent fringe analysis methodology. Essentially, our aim is to answer two problems: can we reliably encode multiple phase information in a single frame, and can we design efficient decoding schemes to extract the individual phases from a single measurement? The multicomponent paradigm has particular relevance for metrological applications, where there is high demand for simultaneous measurement of the 3D components of deformation and strain. However, most existing fringe analysis techniques are capable of only unicomponent phase retrieval. To address this limitation, we designed a digital holographic moire system\cite{12} for encoding multiple phases in a single fringe pattern. Subsequently, we proposed a novel mathematical formulation based on multicomponent polynomial phase modeling\cite{13} to extract the individual phases. We applied this approach with a holographic moire fringe pattern, encoding two different phase distributions: see Figure 3(A). The proposed multicomponent approach reliably extracts the two phases, as shown in Figure 3(B) and (C), as well as the respective estimation errors: see Figure 3(D) and (E). This method enables multicomponent fringe analysis without the requirements for unwrapping and spectral filtering. Furthermore, the ability to estimate multiple phases from a single fringe pattern significantly enhances the robustness of the proposed methods against vibrations and external disturbances, and provides the feasibility to analyze multidimensional deformation dynamics.

Figure 2. (A) Fringe pattern. Estimated phase derivatives with respect to (B) $x$ and (C) $y$ in radians/pixel, and the corresponding estimation errors (D and E) in radians/pixel.

Figure 3. (A) Holographic moire fringe pattern. The estimated (B) first and (C) second phases in radians, and the respective estimation errors (D and E) in radians.
In summary, our methods offer substantial advancements in the field of fringe analysis. Looking ahead, we aim to include more signal processing tools in the domain, to explore significant opportunities for scientific and industrial applications.

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Author Information

Pramod Rastogi
Swiss Federal Institute of Technology in Lausanne
Lausanne, Switzerland

Pramod Rastogi has authored more than 150 scientific papers, and edited six books. He is a fellow of the Optical Society and SPIE, and is a recipient of the SPIE Dennis Gabor Award. He also serves as editor-in-chief of the Journal of Optics and Lasers in Engineering.

Rajshekhar Gannavarpu
University of Illinois, Urbana-Champaign
Urbana, IL

Gannavarpu Rajshekhar is a postdoctoral fellow at the Beckman Institute for Advanced Science and Technology.

References