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New Techniques in Digital Holography

Edited by
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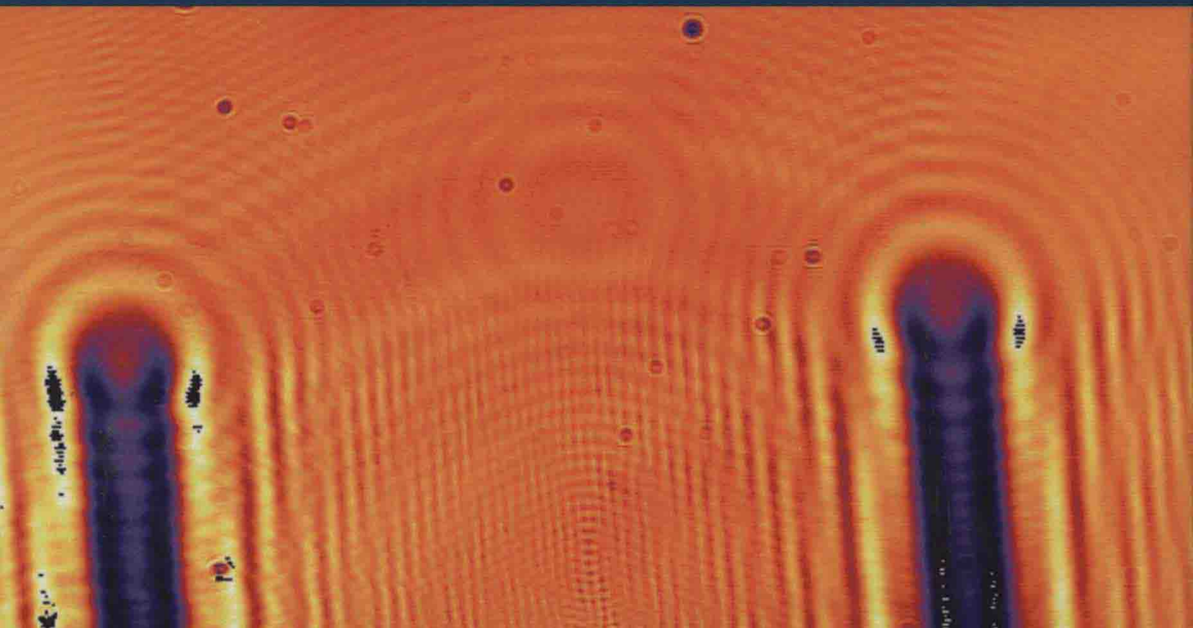

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New Techniques in Digital Holography

Introduction

Holography, the brilliant idea from Dennis Gabor [GAB 48], became "digital" in the early 1970s with the pioneering works of Goodman, Hua and Kronrad [GOO 67, HUA 71, KRO 72]. It took until 1994, for "digital holography" based on array detectors to come about [SCH 94], as a consequence of the important developments in two sectors of technology: microtechnological procedures have made the creation of image sensors with numerous miniaturized pixels possible, and the rapid computational treatment of images has become accessible with the appearance of powerful processors and an increase in storage capacities. From 1994, holography found a new life in the considerable stimulation of research efforts. About 20 years later, digital holography appears to be a mature topic, covering a wide range of areas such as three-dimensional (3D) imaging and display systems, computer-generated holograms, integral imaging, compressive holography, digital phase microscopy, quantitative phase imaging, holographic lithography, metrology and profilometry, holographic remote sensing techniques or full-field tomography. In addition, besides the visible light classically used, light sources including coherent to incoherent and X-ray to terahertz waves can be considered. Thus, digital holography is a highly interdisciplinary subject with a wide domain of applications: biomedicine, biophotonics, nanomaterials, nanophotonics, and scientific and industrial metrologies.

Introduction written by Pascal PICART.

Thus, as actors of this boom, it seemed convenient that we propose a book devoted to special techniques in digital holography. The coauthors aim to establish a synthetic stat of the art of important advances in the field of digital holography. We are interested in detailing advances related to fundamentals of digital holography, in-line holography applied to particle tracking and sizing, digital color holography applied to fluid mechanics, digital holographic microscopy as new modality for live cell imaging and life science applications, long-wave infrared holography, and special techniques in full-field vibrometry with detection at the ultimate limits.

The book is organized into seven chapters. Chapter 1 introduces the basic fundamentals of digital holography, the recording of digital holograms, demodulation techniques to separate the diffraction orders, algorithms to reconstruct the complex object wave, and basic principles of holographic interferometry and phase tomography. Chapter 2 discusses the use of in-line holography for the study of seeded flows; the recent developments permit us to apply this technique in many industrial or laboratory situations for velocimetry, particle size measurement or trajectography. In Chapter 3, the coauthors present new approaches in three-color holography for analyzing unsteady flows. Special techniques to visualize and quantitatively analyze flows up to Mach 10 are presented. The in-line approach based on Wollaston prisms will be discussed and compared to the holographic Michelson arrangement. Chapter 4 is devoted to automation of digital holographic detection procedures for life sciences applications. With the use of partial spatially coherent light sources, the use of a reduced coherence source is of interest for reducing the measurement noise; typical applications are detailed. The coauthors describe specific tools linked to the numerical propagation that are indispensable to process the information correctly, avoid numerical effects and make easier the further processing. The automated 3D detection methods based on propagation matrices with both a local and a global approach are discussed and illustrated on concrete applications. Chapter 5 is devoted to applications of quantitative phase digital holographic microscopy in cell imaging. The most relevant applications in the field of cell biology are summarized. Recent promising applications obtained in the field of high content screening are presented. In addition, the important issue concerning the development of multimodal microscopy is addressed and illustrated trough concrete examples, including combination with fluorescence microscopy, Raman spectroscopy and electrophysiology. Chapter 6 presents digital holography in the long-wave infrared domain. Technology related to sensors and light sources are presented and digital holographic infrared interferometry is detailed and applied to high-amplitude displacements of industrial aeronautic structures. Examples of non-destructive testing (NDT) are also provided. Chapter 7 presents new techniques in the field of vibration measurement; combined off-axis and heterodyne digital holography experiments are presented. In particular, techniques based on high speed and ultimate sensitivity are described. Examples related to life sciences are presented and detailed.

This book is intended for engineers, researchers and science students at PhD and Master's degree level, and will supply them with the required basics for entering the fascinating domain of digital holography.

I.1. Bibliography

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Contents

1

Basic Fundamentals of Digital Holography

The idea of digitally reconstructing the optical wavefront first appeared in the 1960s. The oldest study on the subject dates back to 1967 with the article published by Goodman in *Applied Physics Letters* [GOO 67]. The aim was to replace the "analog" recording/decoding of the object by a "digital" recording/decoding simulating diffraction from a digital grating consisting of the recorded image. Thus, holography became "digital", replacing the silvered support with a matrix of the discrete values of the hologram. Then, in 1971, Huang discussed the computer analysis of optical wavefronts and introduced for the first time the concept of "digital holography" [HUA 71]. The works presented in 1972 by Kronrod [KRO 72] historically constituted the first attempts at reconstruction by the calculation of an object coded in a hologram. At that time, 6 h of calculation was required for the reconstruction of a field of 512 × 512 pixels with the Minsk-22 computer, the discrete values being obtained from a holographic plate by 64-bit digitization with a scanner. However, it took until the 1990s for array detector-based digital holography to materialize [SCH 94]. In effect, there have been important developments in two sectors of technology: since this period, microtechnological processes have resulted in charge coupled device (CCD) arrays with sufficiently small pixels to fulfill the Shannon condition for the spatial sampling of a hologram; the

Chapter written by Pascal PICART, Michel GROSS and Pierre MARQUET.

computational treatment of images has become accessible largely due to the significant improvement in microprocessor performance, in particular their processing units as well as storage capacities.

The physical principle of digital holography is similar to that of traditional holography. However, the size of the pixels in an image detector (CCD or complementary metal oxyde semiconductor (CMOS)) is clearly greater than that of the grains of a traditional photographic plate (typically 2–3 μm, compared with some 25 nm). These constraints impose to take into account certain parameters (pixel area, number of pixels and pixel pitch) which were more or less clear in an analog holography.

This chapter, as an introduction to advanced methods detailed in other chapters, aims at describing the different aspects related to digital holography: the principle of light diffraction, how to record a digital hologram and color holograms, algorithms to reconstruct digital holograms, an insight into the different holographic configurations, special techniques to demodulate the hologram, the basic principle of digital holographic interferometry and a brief discussion on tomographic phase imaging.

1.1. Digital holograms

A digital hologram is an interferometric mixing between a reference wave and a wave from the object of interest. This section presents the basic properties related to a digital hologram.

1.1.1. *Interferences between the object and reference waves*

Figure 1.1 illustrates the basic geometry for recording a digital hologram. An object wave is coherently mixed with a reference wave, and their interferences are recorded in the recording plane H. In digital holography, the recording is performed by using a pixel matrix sensor.