ARTICLE IN PRESS

Optics and Lasers in Engineering ∎ (∎∎∎∎) ∎∎∎–∎∎∎

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

journal homepage: www.elsevier.com/locate/optlaseng

Laser speckle based digital optical methods in structural mechanics: A review

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A R T I C L E I N F O

Article history:
Received 20 November 2015
Received in revised form
13 January 2016
Accepted 10 February 2016

Keywords:
Structural mechanics
Speckle interferometry
Holographic interferometry
speckle correlation
Non-destructive testing

A B S T R A C T

Laser Speckle Correlation, Electronic Speckle Pattern Interferometry and Digital Holographic interferometry have evolved for decades to become relevant techniques in many fields of today's wide spectrum of knowledge and disciplines. Indeed, with today's advances in optics, photonics, electronics and computing there are many important applications for them and strictly speaking there are an almost infinite number of applications that one can think of, as they are non-contact optical techniques that can be used to measure mechanical parameters ranging from a few microns to hundreds of nanometers. In this review we will explore and discuss some relevant applications in structural mechanics in the fields of materials in engineering, biomedical and art preservation and restoration. This work will take the reader from a succinct historical account on the development of these techniques, followed by a brief theoretical description for each one that will then facilitate the introduction of the results chosen as the key applications, ending the review with the conclusions. From the myriad of papers now available in the web, we will only present those that we believe are the most illustrative applications within three lustrum, 2000 to 2015, all set to give a frame that place these optical techniques as mature technologies with an absolute relevance to conduct metrology in many fields.

1. Introduction

The invention of Holography by Gabor [1,2] set the start of a new measuring tool that with time has proved to be a remarkable, powerful and versatile technique to measure. He coined it Holography, a concept that got him the Nobel Prize in Physics in 1971. Gabor proposed a method to record not only the intensities (amplitudes) but also the phase of two overlapping electron beams, one that passed through the microscope setup undisturbed and a second that passed through the specimen under study resulting in a interference pattern. His original experiments were done using an optical source because a sufficiently bright, and coherent electron source was not available at that time. The conceptual basis for holography rests in the basic knowledge of interferometry, i.e., how wave fronts are combined in space at a given time in order to obtains amplitude and phase information from them.

The technique invented by Gabor was devised to seek a reliable way to correct the aberrations inherent in electron microscopes, mainly the spherical aberration which meant that the observed images of angstrom size were defocused. The hologram was recorded on a photographic plate that had to undergo the chemical process needed to develop and fix the film. The object wave front reconstruction used an all optical setup that consisted in illuminating the hologram recorded on the film with a coherent monochromatic beam that worked in the visible part of the electromagnetic spectrum.

The invention of the laser in the late 1950s meant that a brighter and more coherent light beam could be used to reconstruct the object wave front imbedded in the randomness structure of the interferogram recorded in the hologram. The advent of commercially available lasers presented a breakthrough in optical holography, since lasers were highly coherent light sources that could be used to illuminate objects larger than those needed to be looked at using electrons. Optical holography was developed at a really fast pace during the early 1960s. Seminal work on the subject was carried out by Leith and Upatnieks [3], who developed the idea of off-axis configuration, by which the reference and object waves were made to interfere at an angle, rather than having both coming on axis. During this decade an experiment was devised for the image recombination from two holograms taken from the same object but with a deformation introduced on the object between the two takes. Holographic interferometry was invented [4], and a new field in metrology emerged.

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http://dx.doi.org/10.1016/j.optlaseng.2016.02.008
0143-8166/

Please cite this article as: De la Torre IM, et al. Laser speckle based digital optical methods in structural mechanics: A review. Opt Laser Eng (2016), http://dx.doi.org/10.1016/j.optlaseng.2016.02.008

The introduction of a Vidicon camera at the end of the 1960s gave a new and powerful push to the technique, since the holographic film could now be replaced by a non-wet process. A system developed for "real time" holographic interferometry was coined as electronic speckle pattern interferometry [5,6]. This meant that holograms could now be obtained more rapidly and be observed at video rates or in "real time" (50 Hz and 60 Hz, for Europe and North America, respectively). However, the resolution of this type of cameras fell short of the resolution needed in Holography (typically a few lines/mm as compared to 2–4 thousands of lines/mm). But the replacement of the holographic film was there to stay. The combination of new sensors and lasers create a new group of non-destructive testing systems based on the speckle. The ability to track or correlate the speckle in time or space makes it possible to measure in the microns range with a high accuracy. Pulsed and continuous lasers were used to analyze different objects under a wide spectrum of conditions having the same common root: the speckle. Traditional interferometry and phase retrieve algorithms were adapted for these new techniques able to measure over non specular surface's objects. In what follows, we will present the development over the last fifteen years, namely 2000 to 2015, of three optical nondestructive techniques, as they are employed to solve a wide variety of problems in structural mechanics. The reported research in this topic is so diverse and extensive that we will only focus on three applications, viz., key materials in engineering, biomedical studies and art preservation and restoration.

2. Structural studies with NDT: a brief introduction

Since the laser was used in interferometry instead of the classic discharge lamps more than a half century ago, a new kind of measurements were possible. The speckle phenomena once considered as optical noise became a tool as researchers used it to create new techniques to measure the optical phase. An example of this was the holographic film which recorded high frequency interferograms from double exposure tests. These high resolution photographic films showed fringe patterns corresponding to micro deformations in samples such as cantilevers, etc., [7].

Once the digital camera was a reality, it did not take too much time to replace the films for these early digital sensors [8]. However, the use of this technology involved a new challenge due to the sensors' small resolution offered at that time. The available cameras had a resolution of about 256×256 pixels in the best cases. Besides, the bulky analogous to digital converters (ADC) recovered signals up to 8 bits with low signal to noise ratio (SNR) due a complex signal processing hardware not always compatible with all platforms because each camera commonly used a different communication protocol.

These early cameras were however capable to record the first specklegrams, but they could not resolve the high frequency fringes as the holographic film did. The camera's pixel size was bigger than silver halide particles, so all the high frequency information was normally averaged (see Fig. 1).

However, by modifying the aperture size of the optical system, it was possible to match the camera's pixel to the speckle size in order to record a useful specklegram. In order to retrieve the relative optical phase difference coming from the sample's deformation a new series of methods such as correlation by subtraction were introduced. Some other methods were soon introduced to ease the process of obtaining the imbedded optical phase with electronic cameras (normally a CCD), these were: carriers, phase stepping, speckle correlation, spectral transformations and so on [9].

As a result several optical techniques were introduced in a relative short time. This section will briefly describe three laser based techniques: Laser Speckle Correlation (LSC), Electronic Speckle Pattern Interferometry (ESPI) and Digital Holographic Interferometry (DHI), for light sources in the visible range (400–700 nm). Even when these techniques use a laser and correlation algorithms, they have differences in the way they measure structural information making it possible to use them in different kinds of applications. These applications are hereby limited to the structural mechanical analysis in engineering and biological materials, and art work.

2.1. Laser speckle correlation

The Laser Speckle Correlation is one of the very first reported techniques, mainly due to the fact that it can work with low resolution sensors. However, the post processing algorithms require

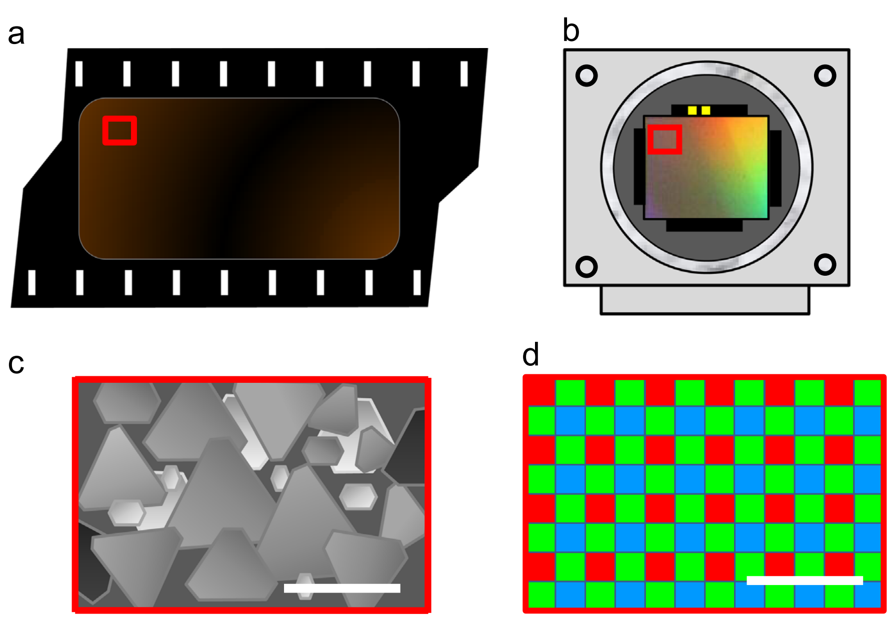

Fig. 1. Recording media (a) holographic film and (b) CCD sensor with a zoom of the (c) silver halides and (d) the pixels. Black bars in (c and d) represent 2 and 80 μm respectively.

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