Optics and Lasers in Engineering 77 (2016) 143–153

Contents lists available at ScienceDirect

Optics and Lasers in Engineering

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

Simultaneous two-axis shearographic interferometer using multiple wavelengths and a color camera

Guillaume L. Richoz, Gary S. Schajer*

Department of Mechanical Engineering, University of British Columbia, Vancouver, Canada

ARTICLE INFO

Article history:
Received 25 March 2015
Received in revised form
19 July 2015
Accepted 19 August 2015
Available online 7 September 2015

Keywords:
ESPI
Shearography
Color camera
RGB
Surface slopes

ABSTRACT

Multi-component measurements in shearography and other applications of Electronic Speckle Pattern Interferometry (ESPI) are typically achieved using multiple optical configurations that are activated sequentially to measure each desired quantity separately. A novel optical setup is introduced here where orthogonal shearography measurements are simultaneously made using a single color-camera imaging multiple monochromatic light sources of different wavelengths. The Red–Green–Blue (RGB) sensors of a conventional Bayer type camera are read separately, thereby providing three independent color signals and independent ESPI phase maps. Orthogonal axis shearography is achieved using a modified shearography interferometer where a dichroic filter is added to provide a second wavelength-dependent measurement. The availability of the two surface slopes gives the opportunity for the data to be summed numerically to give the surface displacement shape. This application is of significant practical interest because the surface displacement measurement can be made under field conditions by taking advantage of the well-known optical stability of shearography measurements. The two simultaneously measured surface slopes also offer the possibility to mathematically compensate for non-uniformity and non-orthogonality in the image shear caused by mirror non-flatness and/or mirror misalignments.

1. Introduction

Electronic Speckle Pattern Interferometry (ESPI) is an imaging technique that uses coherent laser light to visualize and quantify small surface displacements of an object [1,2]. The technique has been used in a wide range of applications in deformation and vibration analysis, Non-Destructive Testing (NDT), quality control, design validation and optimization, and in fluid flow visualization [3–5]. With modern data processing systems, a large amount of experimental data can be processed and displayed effectively in real time.

The use of a color camera allows simultaneous and spatially aligned measurements of multiple independent signals, one for each measured color. This is possible because the sensor of a typical Bayer style color camera contains interlaced sets of color sensitive pixels, Red, Green, and Blue (RGB) [6]. Each of the colored pixels can be read separately, thus allowing independent and simultaneous measurement of three different colored speckle images. Such simultaneous measurement is particularly valuable for surface vibration and other time-varying measurements. Techniques exist for making ESPI measurements from a single optical image [7], thereby allowing high-speed sequential acquisition of ESPI data. Here, three independent measurements are made simultaneously, thus automatically making them coordinated in time. In addition, the three speckle images are mutually aligned on the Bayer sensor, so they are also automatically coordinated in space. All of these features extend the range of use of ESPI measurements and simplify optical design.

Shearography is a popular measurement technique because its parallel path optical configuration and its low sensitivity to rigid-body motions makes it relatively stable compared with other ESPI measurement types [8,9] and thus more practical for field use. The evolution of experimental setups described in the literature represents well the progress of the shearography technique. In 1997, Aebischer, and Waldner presented a simple optical set-up with three light sources arranged in a particular symmetry and an associated procedure which allows accurate isolation of all six displacement derivatives [10]. Sennhauser et al. developed a multi-wavelength speckle pattern shearing interferometer for the determination of two-dimensional strain distributions [11]. The progress of shearography also opened the doors of new applications for the technique. Shakher and Nirala used shearography for measuring the temperature profile inside a gaseous flame [12].

This paper illustrates the use of multiple separate-color measurements to achieve multi-axial shearographic measurements. In the shearography setup introduced here, two modified Michelson

* Corresponding author.
E-mail address: schajer@mech.ubc.ca (G.S. Schajer).

http://dx.doi.org/10.1016/j.optlaseng.2015.08.007
0143-8166/

interferometers are combined within a single interferometer arrangement, one with a mirror tilted in the *x*-direction to indicate the x-rotation of the specimen surface, and the second with a mirror tilted in the *y*-direction to indicate the y-rotation. This two-axis interferometer arrangement additionally gives the possibility of reconstructing the deformed shape of the measured object by numerical summation of the two axial surface slopes.

A novel multi-wavelength shearography setup for full-field quantitative measurements of surface slope is presented here. The construction of the shearography system is described and its capabilities are demonstrated through some example measurements.

2. Multi-wavelength shearography

Fig. 1 illustrates a conventional shearography measurement arrangement using a modified Michelson interferometer [1–3]. In this arrangement, a camera views an object illuminated by coherent monochromatic light source through the interferometer. The beam splitter and mirror assembly provides two alternative optical paths. If the mirrors were exactly aligned, the two paths would recombine to image the same points on the object. However, a deliberately induced tilt in one of the mirrors causes a lateral shift in one path so that the camera views two slightly displaced images. In this way, each pixel on the camera receives light from two adjacent points on the illuminated object. The light from the pairs of points interfere on the diffraction plane, or camera pixels in that case, to produce the measured speckle pattern. For this optical arrangement the measured phase map mostly corresponds to the out-of-plane surface slope in the direction of the image shift.

Multi-direction shearography is made possible by the addition of a dichroic filter as shown in Fig. 2 The inclusion of this filter creates two shearographic interferometers within one optical setup. The target object is simultaneously illuminated by three coherent laser sources of different wavelengths, here red ($\lambda = 660$ nm), green ($\lambda = 532$ nm) and blue ($\lambda = 473$ nm). The light passes from the object through the double interferometer to a color camera that is able to record each color separately. This color separation allows separate measurement of the two shearing directions and hence separate identification of the surface slopes. The surface slope being measured in two different directions, orthogonal in that case, allows use of a mathematical procedure to correct for non-uniform shears and small mirror misalignments. Green and blue are used redundantly here to measure the same surface slope in order to identify the phase datum using the “Two-Wavelength” method [10, 11-15].

A Bayer type camera simultaneously records three independent colored signals. These can be used for simultaneously measuring deformations in two or potentially three different directions. Cross-talk between color responses exists, but can be corrected by calibration [15], thus producing three independent measurements.

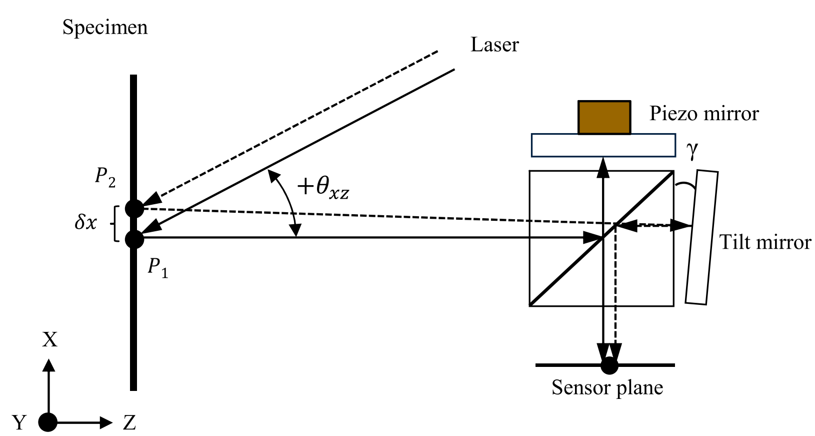

Fig. 1. Optical configuration of an out-of-plane shearographic system.

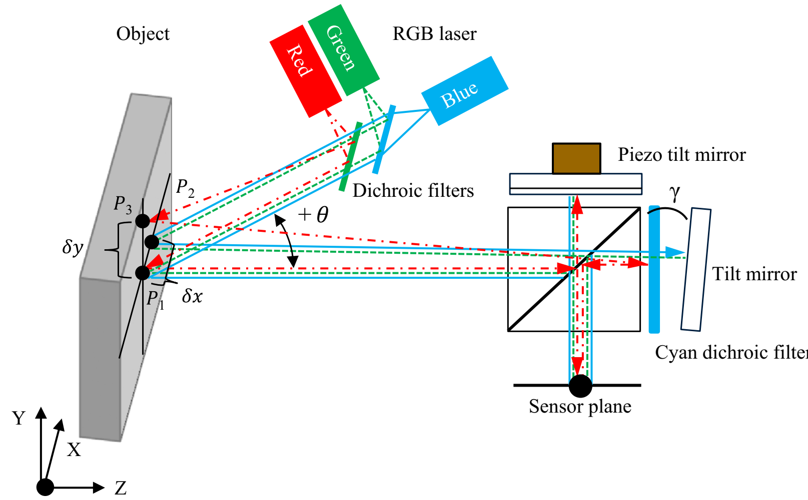

Fig. 2. Optical configuration of a two-axis shearographic system.