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Full field displacement measurement by double symmetrical illumination with diode lasers through a pair of double exposure reflection holograms

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ABSTRACT

Compact and stable phase stepping interferometer for shape and full field displacement measurement in static and in "real time" operation mode is presented. Double symmetrical illumination of the object in two orthogonal planes with diode lasers, emitting in NIR (790 nm and 830 nm), through a four-exposure reflective holographic optical element (Denisiyk's volume reflection holograms of a reference plane) is applied. The proposed four channels one-beam interferometer is very compact, as the diode lasers without collimators and spatial filters are used directly for reconstruction of the reference planes from a pair of double exposure reflection holograms and for object's illumination through the same holographic optical element. Phase stepping is introduced simply by precise increments of the diode lasers current. By introduction of removable sinusoidal phase gratings and removal of the holographic optical element, the system operates as a single-shot fringe projection profilometer for shape measurement that is essential for precise estimation of displacement vector's components. The proposed system is very stable against external noise, produced by vibrations, temperature changes, air flows, as well as against the influence of object's "rigid body" motion, as the compact and low weight interferometer can be stably fixed directly onto the measured construction.

1. Introduction

Determination of strains, stresses and bending moments in experimental and fracture mechanics requires full field (in-plane and out-of-plane) displacement measurement. Precise knowledge of the displacement vector's components and their derivatives is essential for quality control, failure prediction and early detection of critical zones with abnormal mechanical behavior of loaded objects due to voids, cracks, fatigues and other stress concentrators. The most appropriate techniques to perform the displacement measurement are the non-contact coherent optical methods [1–4], as fringe projection, digital holographic interferometry, digital image correlation techniques (DIC), and digital electronic speckle pattern interferometry (DESPI). As a rule, a double symmetrical illumination in two orthogonal planes has to be applied. The first, second and mixed derivatives of the measured components $w(x,y)$, $u(x,y)$ and $v(x,y)$ of the displacement vector L at each point of the deformed or rotated object's surface are the entries for calculation of the in-plane normal strain εx and εy, the shear strain γxy, the in-plane rotation ωz, as well as of the out-of-plane rotation (tilt), stresses and bending moments. Correct estimation of the displacement vector components $w(x,y)$, $u(x,y)$ and $v(x,y)$ in the case of real 3D objects requires precise measurement of the object's surface [5]. Fringe projection profilometry with a phase-shifting or Fourier analysis has to be applied [6–8]. In addition, to study objects with non-linear mechanical response or to measure transient effects and dynamic states the data of the object's deformed state should be provided in "real time". That is why the single shot Fourier transform method has become a popular choice for phase retrieval and it is widely used for solving different tasks in applied and fracture mechanics. The pointwise temporal phase stepping (TPS) technique, however, as a local phase retrieval approach, ensure better sensitivity and measurement accuracy than the global Fourier algorithm at the expense of acquisition of at least three fringe patterns. Different solutions have been proposed to implement the phase stepping technique in real time as spatial phase stepping (SPS) [9–11], multiwavelength electronic speckle pattern interferometry [12], speckle pattern interferometry with the Hilbert transform method [13], double-exposure phase calculation method [14] and others. However, the measurement of transient effects in "real" time usually leads to decreased sensitivity, accuracy and resolution, as it was shown by comparative analysis between TPS and SPS, presented in [11]. Quite different and interesting approach has been proposed in [15,16]. The TPS is applied to the non-loaded state of the object with five steps and only one fringe pattern at a zero phase shift is used for phase retrieval in the loaded state. The mandatory requirement for implementation of such a

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measurement is stability of the interferometric set-up against external noise, produced by vibrations, temperature changes, air flows, etc.

The goal of the present work is to create compact and stable phase stepping interferometer for full field displacement measurement in static and ‘‘real time’’ operation mode in laboratory and working conditions. The task is solved by double symmetrical illumination of the object in two orthogonal (vertical and horizontal) planes with four temperature stabilized diode lasers, emitting in NIR at different wavelengths for each of the planes, through a removable four-exposure reflection holographic optical element (HOE), which reconstructs four reference planes. Interference and polarization filters ensure parallel data acquisition in the four separate channels of the system. The same diode lasers are used for measurement of the shape of the non-loaded object by illumination through removable sinusoidal phase gratings.

2. Optical arrangement and operation of the system

Optical set-up of the digital phase stepping speckle pattern interferometer for the full field displacement measurement is presented in Fig. 1. The basic element of the system is the removable four-exposure reflective HOE (RRHv&RRHh), which is composed from a pair of double-exposure Denisyuk's reflection holograms of a diffusely reflecting reference plane. Optical arrangement for recording reflection hologram with He–Ne laser for one of the channels is shown in Fig. 2, and the scheme for its reconstruction with different wavelengths in Fig. 3. It should be pointed out that the volume reflection holograms, recorded with opposite light beams, according to the Denisuyk's method [17], found application in optical metrology from the very beginning of the holographic interferometry for double exposure interferometry, pulse recording of transient and dynamic processes, for time-averaged and real time interferometry [1]. The main advantage of using a reflection hologram is implementation of an one-beam interferometer, as the object is directly illuminated through the holographic plate. The beam reflected from the object's surface interferes with the reference beam reconstructed from the corresponding hologram. This results in considerable simplification of the optical set up due to the minimized number of the used optical and mechanical elements. In our case the four-exposure reflective HOE is formed as a ‘‘sandwich’’ structure from two double-exposure volume reflection holograms of one and the same diffusely reflecting flat screen (the second exposure is made after rotating the plate at 180 degrees). The holograms are recorded with a He–Ne laser ($\lambda = 632.8$ nm) onto high resolution silver halide light sensitive plates HP-650, laboratory production of IOMT-BAS [22]. Reconstruction of the holograms at the wavelengths in NIR (790 nm and 830 nm) is achieved after appropriate swelling of the developed plates [19]. Reconstruction with different wavelengths from the wavelength of recording produces aberrations [23,24], that could be partly compensated by changing the distance l and angle of illumination, being 100 cm and 30° in recording at wavelength 632.8 nm and 20 cm and 36° in reconstruction with diode lasers respectively. Nevertheless,

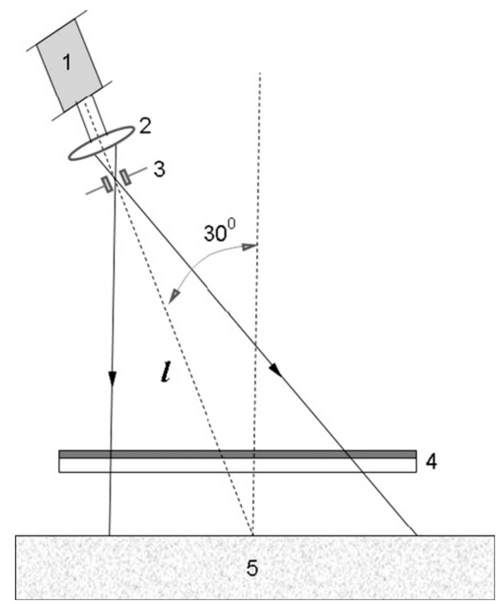

Fig. 2. Optical arrangement for recording reflection hologram for one of the channels, where: (1) is the HE–Ne laser, (2) beam expander (micro objective), (3) spatial filter, (4) holographic plate, (5) diffuse light reflective metal screen.

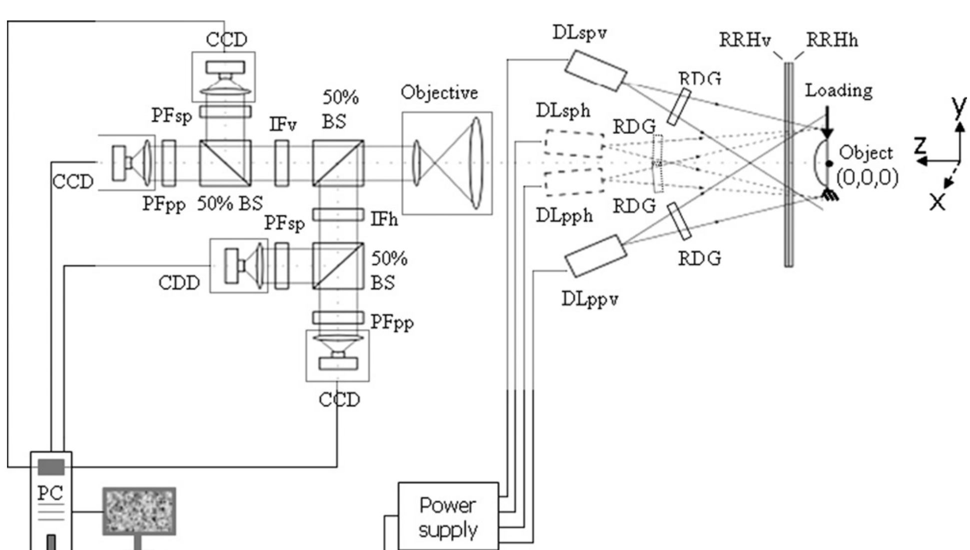

Fig. 1. Optical set-up of four channels digital phase stepping speckle pattern interferometer where: BS is a beam splitter; DLspv—diode laser in vertical position *s* polarized; DLppv—diode laser in vertival position p polarized; DLpph—diode laser in horizontal position *p* polarized; DIsph—diode laser in horizontal position *p* polarized; RRHv—removable refraction hologram for vertical position; RRHh—removable refraction hologram for horizontal position; Ifh—interference filter for horizontal position; Ifv—interference filter for vertical position; PFsp—polarizing filter s polarization; PFpp—polarizing filter *p* polarization; RDG—removable sinusoidal phase grating.