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Investigation of crack origin in hybrid components with two-color digital Fresnel holography

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Abstract. The paper presents a two-color digital holographic interferometer. The set-up is devoted to the investigation of crack origin in hybrid industrial electronic components. Optical configuration and algorithms to recover the optical phase of two-color digitally encoded holograms are described. The method is based on a spatial-color-multiplexing scheme in which holographic reconstruction is performed using a spectral scanning algorithm. Experimental results exhibit in-plane and out-of-plane non uniform deformations that are the probable cause of the cracking of the component.

1 Introduction

Classical holographic interferometry has proved in past decades to be a very useful industrial tool for the measurement of full field surface deformations of naturally rough objects [1]. Digital holography originated in the early 1970's and became properly available in the last decade [2] with high speed CCD cameras and the increasing power of computers. Recently, it has been demonstrated that digital Fresnel holography offers new opportunities for metrological applications: examples include object deformation [2], surface shape measurement [3] and twin-sensitivity measurements [4]. Recently we demonstrated some opportunities for simultaneous two-dimensional metrology by use of digital color holography and recording with a stack of photodiode sensor [5]. This paper presents an alternative method in which the recording is performed simultaneously along each wavelength by a two-color spatial multiplexing of the encoded object. In order to compensate the wavelength dependence of the pixel pitch in the Fresnel transform and to save the physical horizon of the object, we present a spectral scanning algorithm based on the Fresnel transfer function of the free space propagation. Application of the proposed method is demonstrated through an investigation of mechanical causes of cracks inside a capacitance of an hybrid industrial PCB component.

2 Theory

In digital holography, numerical reconstruction of digitally encoded holograms is performed by use of a discrete version of the Fresnel diffraction formulae, which is given by Eq. 1:

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$$U(X,Y,d_r)=\frac{jd_r}{\lambda}\int_{-\infty}^{+\infty}\int_{-\infty}^{+\infty}H(x,y)\exp\left[\frac{j\pi}{\lambda d_r}\left((X-x)^2+(Y-y)^2\right)\right]dxdy \tag{1}$$

where d_r is the distance between the diffracted field and the recording plane, λ is the wavelength of light and H is the hologram at the recording area. The recorded hologram is an interferometric mixing between the reference wave $r(x,y)$ and the object wave $O(x,y)$, such as (* means complex conjugate)

$$H=|r|^2+|O|^2+Or^*+O^*r \tag{2}$$

Note that the reference wave is often an uniform plane wave, so that $r(x,y)=a_r\exp(2j\pi(u^{\lambda}_0x+v^{\lambda}_0y))$, with $(u^{\lambda}_0,v^{\lambda}_0)$ being its spatial frequencies, for a given wavelength λ. The expansion of Eq. 1 leads to the well known Fresnel transform [1]. Generally, object reconstruction in digital holography is based on the use of Fresnel transform associated with a zero-padding [6]. Note that the Fresnel approximation transforms the diffraction formulae into a Fourier transform which can be numerically implemented with FFT algorithms. The sampling pitches of digital holograms computed from the Fresnel transform are given along $\{x,y\}$ directions by $\Delta\eta = \lambda d_r/Kp_x$ and $\Delta\xi = \lambda d_r/Kp_y$. It is clear that if the wavelength changes, then the sampling pitch also changes [7]. However, the computation of holograms along two wavelengths needs to respect a fundamental property: the size of the object must be conserved and the number of sampling data point must be independent of the wavelength. Then, a simultaneous two-dimensional measurement based on two-color holography will be possible only if it is possible to perfectly separate the contributions of each component of a 3D movement. For this, the size of each hologram along each wavelength must be quite similar during the reconstruction process in order to get a perfect pixel to pixel superimposition. The way to get invariance of the pixel pitch is to compute Eq. 1 as a convolution formulae. In such equation, the convolution kernel is the Fresnel impulse response of free space propagation given by:

$$h(x,y,d_r)=\exp\left[\frac{j\pi}{\lambda d_r}\left(x^2+y^2\right)\right] \tag{3}$$

With the computation of Eq. 1 as a convolution formula using a double FFT method, the pixel pitch in the reconstructed plane remains invariant and is equal to that of the detector, whatever the wavelength. Thus, this strategy is the most appropriate for digital color holography. Several algorithms have been developed in this sense [8,9]. In terms of spatial frequency bandwidth, it is necessary that the bandwidth of the convolution kernel cover at least the full bandwidth of the object. If the object bandwidth is greater than that of the kernel, the numerical reconstruction must be implemented with a scanning of the spatial spectrum. In this case, one has to compute a filter bank the role of which is the scanning of the useful object bandwidth in order to allow the reconstruction of the object. The number of scanning is related to the bandwidth to the kernel. Consider the relation between spatial localization and spatial frequency: to any spatial frequency $\{u_0,v_0\}$ in the hologram spectrum corresponds a spatial localization $\{\lambda d_r u_0, \lambda d_r v_0\}$ in the reconstructed object plane. Because of the finite extension of the recording, the kernel bandwidth only allows the reconstruction of an object region with a size of $(Np_x \times Mp_y)$ which is the same size as the detector area. If Δu_{object} is the bandwidth of the object and Δu_{kernel} that of the kernel, in the x direction, then the number of scanning is given by their ratio, leading to the ratio between object size (ΔA) and detector size (Np_x), as $n_x=\Delta u_{\text{object}}/\Delta u_{\text{kernel}}=(\Delta A/\lambda d_r)/(Np_x/\lambda d_r)$ giving $n_x=\Delta A/Np_x$. A similar relation holds for the vertical direction y with number n_y. So, if the real object is greater than the detector area, the reconstructed object will be obtained by a juxtaposition of adjacent regions. The size of the full reconstructed object will be $n_yM \times n_xN$ and needs high memory allocation during the computation. To reconstruct a region of the object centred at spatial coordinate $\{x_i,y_i\}$ with spatial extension of $(Np_x \times Mp_y)$, one has to compute the spatial frequency associated to this zone, i.e. $\{u_i,v_i\} = \{x_i/\lambda d_r, y_i/\lambda d_r\}$. The spectral filter must then be centred at frequency $\{u_i,v_i\}$ in the hologram spectrum. The centring of the filter is performed by modulating the convolution kernel of Eq. 2, according to $h_i(x,y,d_r) = h(x,y,d_r) \times \exp[+2j\pi(u_i x + v_i y)]$. Thus, the transfer function associated to this convolution kernel is $G_i(u,v,d_r) = G(u-u_i, v-v_i, d_r)$ where $G(u,v,d_r)$ is the Fourier transform of $h(x,y,d_r)$. The useful spatial frequencies of the filter bank are given in x and y directions by $\{u_i,v_i\} = \{u_0^\lambda + k_x Np_x/\lambda dr, v_0^\lambda + k_y Mp_y/\lambda d_r\}$, with $k_x \in \{-(n_x-1)/2, +(n_x-1)/2\}$ and $k_y \in \{-(n_y-1)/2, +(n_y-1)/2\}$.

3 Illustration of the algorithm principle

The principle of the spectral scanning algorithm can be understood through the spatial frequency analysis. Consider the Fourier transform (FT) of the recorded hologram:

$$E(u,v) = FT[H(x,y)](u,v) = A(u,v) + C(u-u_0, v-v_0) + C^*(u-u_0, v-v_0) \tag{4}$$

with $A=FT[|r|^2+|O|^2]$ and $C=a_r FT[O]$. The transfer function associated to the convolution kernel, $G(u,v,d_r)$ is localized at the center of the power spectrum. Fig. 1 illustrates the situation in the case of a circular object. On the left is represented the spatial frequency spectrum in which the useful information is localized in the lower left corner (+1 order of hologram) and the useful bandwidth is $\Delta u_{\text{object}} \times \Delta v_{\text{object}}$. On the right is represented the spatial spectrum of the convolution kernel, which useful bandwidth is $\Delta u_{\text{kernel}} \times \Delta v_{\text{kernel}}$ and is localized at the center of the spectrum. Thus the convolution algorithm will reconstruct a part of the object only if the spatial bandwidth of the kernel is localized in the region around frequencies (u_0,v_0).

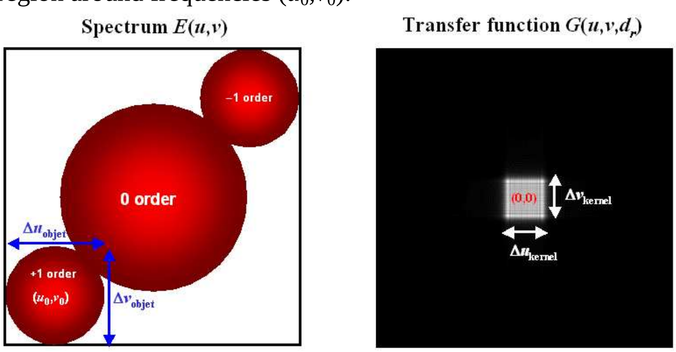

Fig. 1. Spectral analysis of the reconstruction algorithm

When the spatial bandwidth is shifted to this region, using the modulation of the kernel, the algorithm reconstructs a parcel of the object as illustrated in Fig. 2, left. Using a full scanning of the spectrum, the full object can be reconstructed by the juxtaposition of all the adjacent regions. Fig. 2, right, shows the object reconstructed with a $n_x \times n_y = 4\times6$ spectral scanning of the spectrum of the left part of the figure. The object is a 2 euro coin and the white lines indicate the limits of each reconstructed sub-image.

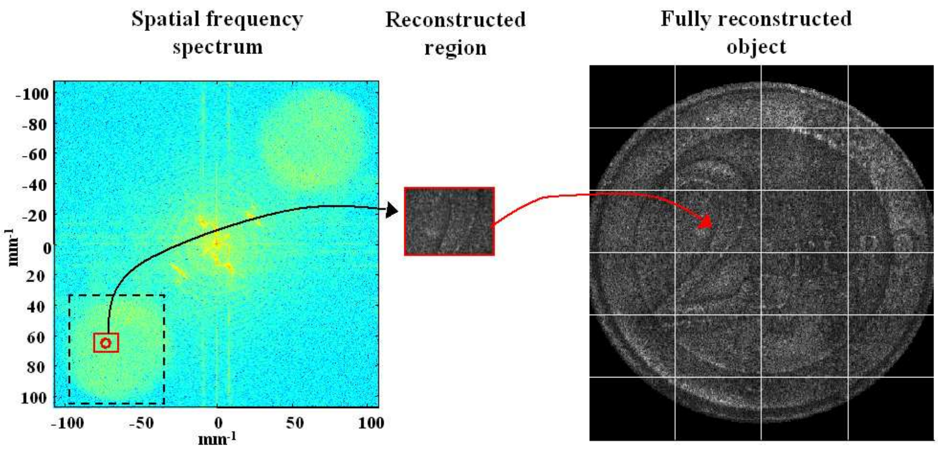

Fig. 2. Reconstruction of the object with the spectral scanning algorithm

This strategy is used in the following sections to reconstruct two-color digital holograms for simultaneous two-dimensional deformation measurements.

4 Experimental set-up

Application of the proposed method is demonstrated through an investigation of mechanical causes of cracks inside a capacitance of an industrial PCB component. The component (capacitance) is cracked during the clamping of the PCB inside its electronics box. The investigation of the causes of this anomaly is made possible since digital holography is well adapted for contact less metrology and micro deformation measurements. Fig. 3 shows the component under interest and the region that is inspected by the two-color digital holographic set-up. The studied field is the circular zone which is 15mm in diameter, containing the clamping zone and the component of interest. The proposed algorithm for the object reconstruction generates a set of 3×3 adjacent sub-images along each color. The PCB is placed at 900mm from the sensor (monochrome CCD, 1024×1360 pixels with 4.65µm pitches). The mechanical simulation of the clamping is realized by use of a progressive loading of the rear panel of the PCB through the clamping region. This reproduces with a very good fidelity the real industrial situation.

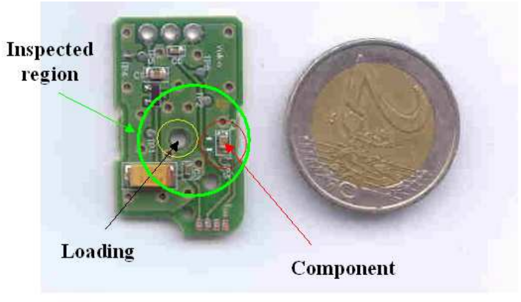

Fig. 3. PCD component under test

Fig. 4 shows a schematic of the optical set-up which includes two cw lasers (green, *G*, at 532nm and red, *R*, at 632.8nm). The two object beams are collimated and illuminate the PCB with two symmetrical angles ($\theta_R=-\theta_G=\theta$) thus giving a 2D sensitivity. The set-up is then sensitive to the in-plane and out-of-plane displacement of the object. A Mach-Zehnder interferometer produces the mixing between the two duplets of colors. Each laser beam is split into an illuminating beam and a reference beam which are co-polarized for each wavelength. The smooth and plane reference waves are produced through the two spatial filters (SF1 and SF2). Thus each reference wave is the spatial carrier of each hologram.

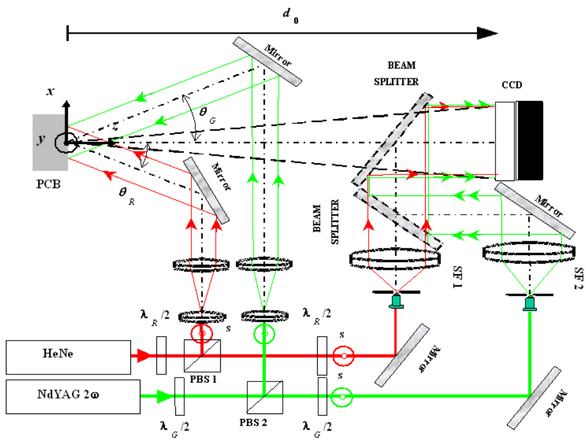

Fig. 4. Holographic set-up using two wavelengths: M: Mirrors, BS: beam splitter; SF: spatial filter

Since the monochrome sensor is not able to record the two colors simultaneously at each pixel, the spatial frequencies of the reference waves (*R* and *G*) are adjusted so that the two-color holograms are spatially multiplexed in the field of view. Thus, the off-line holographic recording is carried out using the two spatial filters in which each collimating lens is displaced out of the afocal axis by means of two micrometric transducers (not represented in Fig. 4). Consider that the object produces a 3D displacement vector according to:

$$\mathbf{U}=u_x\mathbf{i}+u_y\mathbf{j}+u_z\mathbf{k} \tag{5}$$

where $\{u_x,u_y,u_z\}$ are the displacement fields. Taking into account of the illumination geometry, the phase changes measured along each color are given by:

$$\Delta\varphi_R=\frac{2\pi}{\lambda_R}\left[\sin\theta u_x-(1+\cos\theta)u_z\right] \tag{6}$$

and

$$\Delta\varphi_G=\frac{2\pi}{\lambda_G}\left[-\sin\theta u_x-(1+\cos\theta)u_z\right] \tag{7}$$

Then the weighted sum and difference of the phase changes allows respectively extraction of the z and x components, according to:

$$u_z=-\frac{\lambda_R\Delta\varphi_R+\lambda_G\Delta\varphi_G}{4\pi(1+\cos\theta)} \tag{8}$$

$$u_x=\frac{\lambda_R\Delta\varphi_R-\lambda_G\Delta\varphi_G}{4\pi\sin\theta} \tag{9}$$

5 Experimental results

The optical phase changes between loadings of the PCB can be computed and since the physical object horizon is saved, differences between red and green phase changes can be computed in order to get the 2D measurement. The full procedure needs the recording of 90 two-color holograms. Fig. 5,6 show the in-plane and out-of-plane displacement fields obtained after processing of the holograms. Note that the capacitance is localized in the region where the flexion is maximum.

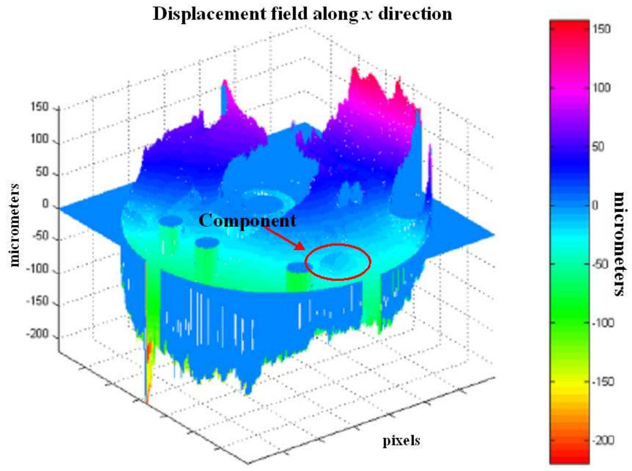

Fig. 5. Displacement field along the *x* direction

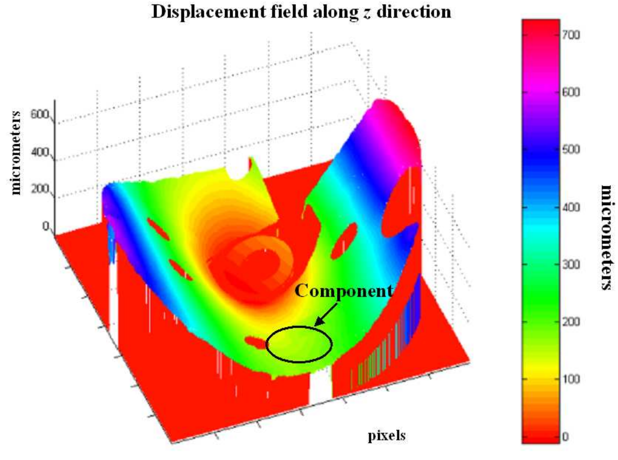

Fig. 6. Displacement field along the *z* direction

After numerical processing of these results, Fig. 7,8 show the region of the component under interest which exhibit high non uniform deformations.

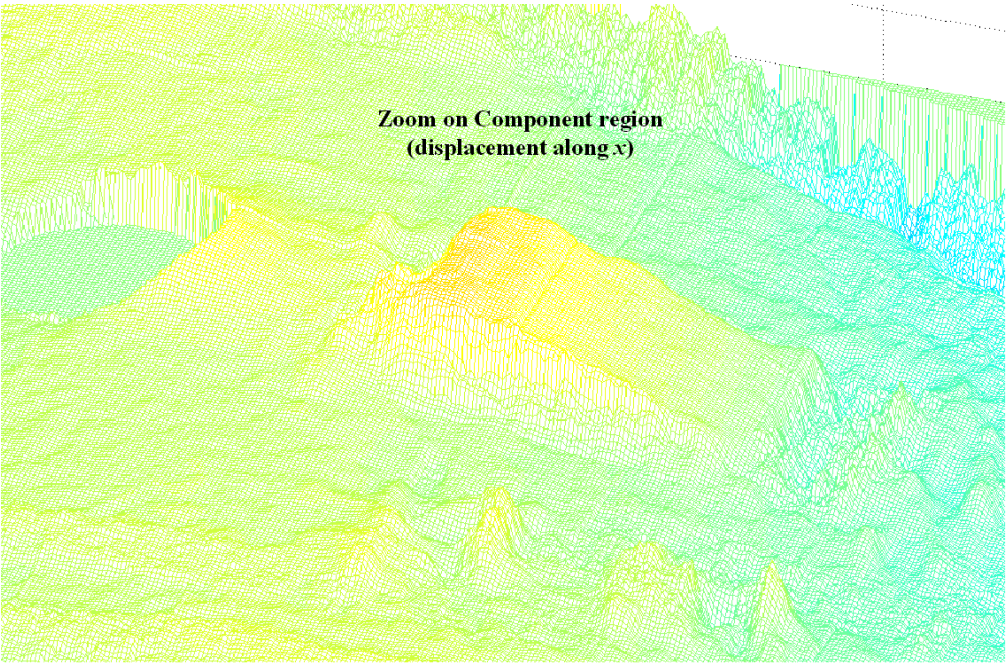

Fig. 7. In plane displacement field in the region of the capacitance after post processing

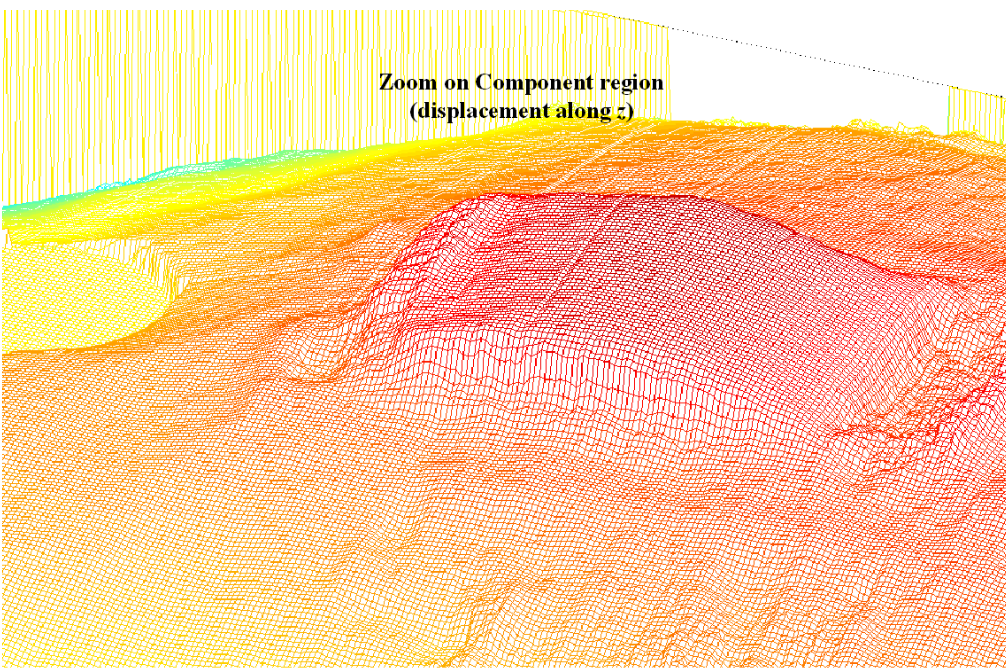

Fig. 8. Out of plane displacement field in the region of the capacitance after post processing

These non uniform deformations are the probable cause of the cracking of the capacitance.

6 Conclusion

The paper has presented a two-color digital holographic setup and method for simultaneous two-dimensional metrology. Experimental results are presented in the case of the investigation of mechanical causes of cracks inside a capacitance of an industrial PCB component. The two-color holographic set-up gives then opportunities for a thorough understanding of causes of cracks inside the capacitance of the industrial PCB component.

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