Electronic Laser Speckle Interferometer for Displacement Measurement using Digital Image Processing Technique

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***Abstract*—Digital speckle image correlation techniques have been successfully proven to be an accurate displacement analysis tool for a wide range of applications. In this paper, a new Electronic Laser Speckle Pattern Interferometer based on Michelson interferometer is designed. An object beam back scattered of an object surface and a reference beam, originating from the same laser light source are superimposed on a charge couple device and form the interference fringe pattern (speckle gram). Subtraction of speckle pattern before and after deformation of aluminum plate gives the measurement of displacement by using fringe analysis with a suitable image processing algorithm.**

***Index Terms*—Digital image correlation, speckle, displacement/deformation measurement**

I. INTRODUCTION

Speckle interferometry has always been paid much attention because of its many advantages such as non-contact, high-accuracy and full-area etc [1]. A speckle pattern is generated when an object with a rough surface is illuminated with a highly coherent source of light such as laser. In the past, speckles were viewed as a disturbance to be suppressed or eliminated. However, measurement based on the laser speckle phenomenon has now become an important subject of optical metrology for full-field NDE (Non destructive Evaluation).The speckle techniques can be classified into three broad categories: speckle photography, speckle interferometry and speckle shear interferometry. Speckle photography [2] includes the methods where positional changes of the speckle are monitored. Speckle interferometry [3] on the other hand includes methods that are based on the measurement of phase changes. Instead of the phase change, we measure its gradient, the method falls into the category of speckle shear interferometry or shearography [4]. The developments in electronic detection and processing further added wings to Electronic Speckle Pattern Interferometry (ESPI) or TV Holography [5]. Full-field laser NDE techniques are based on the optical effect of interferometry. If a rough surface is illuminated by laser light, the light will be scattered back from every illuminated object point (Fig.1).

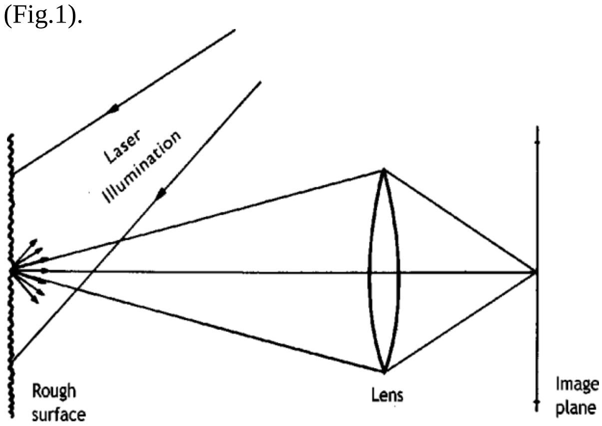

Figure 1. Basics for speckle image formation

If the object is viewed by an eye or the camera, the object surface seems to be covered with bright and dark spots, which are called speckle. These speckles result from the path differences of the light emitted by the laser and reflected to the camera via different surface points.

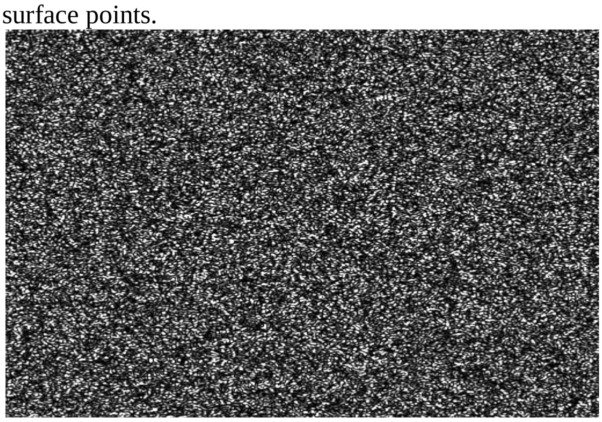

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Figure 2. Speckle pattern

The scattered waves interfere and form an interference pattern. This phenomenon is called the speckle effect. In white light illumination, this speckle effect is difficult to observe because of lack of coherence. The speckle pattern is characterized by a random intensity and phase distribution. It is fundamentally a statistical process [6]. The intensity I is distributed according to the probability density function of a fully developed, polarized speckle field as follows:

$$P(I)=1/\langle I\rangle \exp\{-I/\langle I\rangle\}, \quad I\geq 0 \qquad (1)$$

where I is the mean intensity value. The intensity I follows a negative exponential distribution (Fig.3).

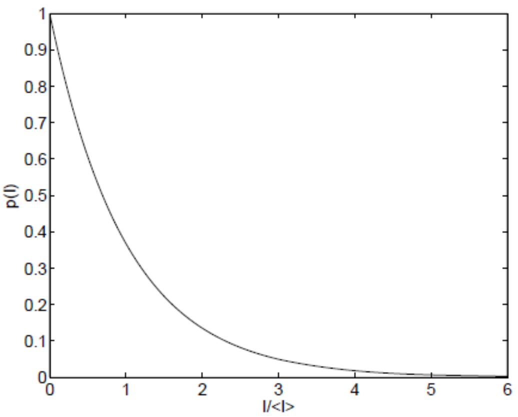

Figure 3. Intensity distribution of speckle pattern

If the statistical properties of the speckle pattern are determined by the size of the illuminated spot, the pattern is called objective. Instead if the statistical properties of the speckle pattern are determined by the aperture of the imaging system, the pattern is called subjective. For the case of a rectangular aperture the in-plane speckle width is defined as:

$$\sigma_{x,y} = \lambda L / D \qquad (2)$$

where λ is the wavelength of the light, L is the distance between the aperture and the detector and D is the width of the rectangular aperture. The speckle length is defined as [6]

$$\sigma_{z} = 7.31\lambda\{L/D\}^{2} \qquad (3)$$

This means that the speckles have the shape of a cigar, since they have a larger size in the z-direction than in the x- and y-direction, unless for very large numerical apertures. The basic importance of the speckle size in metrology lies in the fact that it has to be adjusted to the resolution of the detector not to introduce systematic errors into the analysis.

II. Experiemental Setup

Digital speckle interferometry measures the displacement based on the principle of Michelson Interferometer [7] as shown in Fig.4. The light source is a 5-mW laser diode at the wavelength λ=680 nm. A lens is used to increase the laser divergence and the surfaces are made of aluminum plates.

The scattering angle is typically wide, such surfaces do not need to be exactly aligned and a polished glass plate with partial metal coating on one face as a beam splitter. One of the aluminum plates is deformed by pushing a mechanical tip (micrometer) on its rear side and it should not exceed a few microns for avoid many fringes. The beam splitter split the laser beam into two beams, each of which falls on different surfaces [8].For these conditions there are two overlapping images of the diffusing surfaces on the screen, each being a speckle field. Arm lengths adjusted such a way that the optical path difference is within the coherence length of the source, equalizing the distance between the diffusers and the beam splitter.

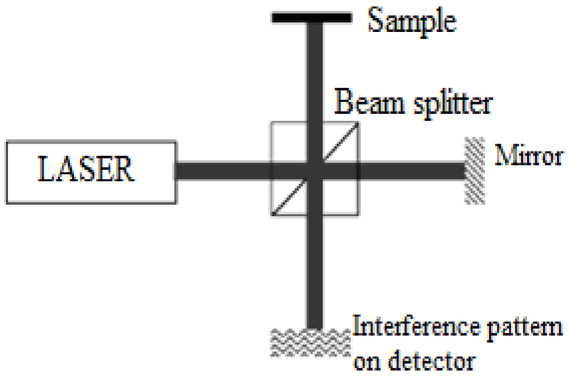

Figure 4. Michelson interferometer

The two fields interfere, although the resulting intensity distribution still appears as a speckle pattern due to the random nature of the interfering fields and thus no fringe is visible. Because of the double pass in reflection, the actual path difference is: (x,y)=2Δ(x,y)λ/2, so that the local field is in phase opposition. The condition of phase opposition is that path difference is an odd multiple of λ /2, or equivalently the displacement is Δ(x,y)= (λ/ 4) (2N+1), where N is an integer.

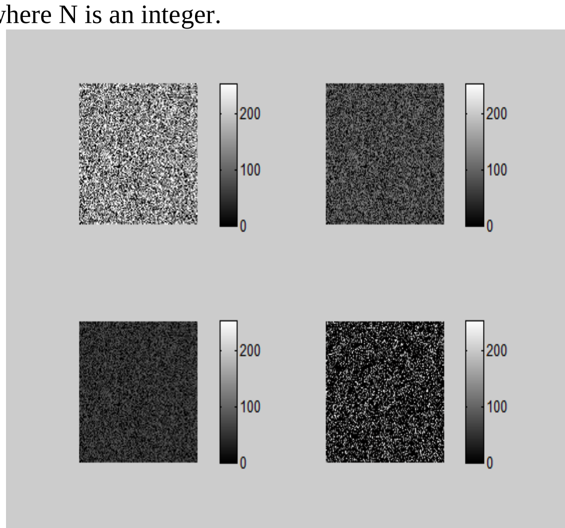

Figure 5. Speckle pattern & subtracted fringe

On the other hand the intensity of the speckle grain is unchanged when path difference is an even multiple

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of λ /2, so that the displacement is $\Delta(x,y)= (\lambda/2)$ N. The speckle correlation is carried out by storing an image while the object is in its initial state and subtracting the subsequent frame from this stored frame, displaying the difference on the monitor. When the object is subjected to some loading or excitation, the correlated areas appear black while the uncorrelated areas would be bright, resulting in a fringe pattern. The fringes represent contours of constant displacement of the object points. The theory behind the fringe formation is as follows [9].

Let the O_1 and O_2 represent the undeformed and deformed object waves, which are written as

$O_1(x,y) = |O(x,y)| \exp[-i\varphi(x,y)]$ …….(4)

$O_2(x,y) = |O(x,y)| \exp[-i \varphi (x,y) + \delta]$ ……. (5)

where δ is the phase change due to displacement or deformation of the object. The intensity due to superposition of these two waves is:

$$I(x,y) = |O_1(x,y) + O(x,y)|^2 = O_1O_1^* + O_2O_2^* + O_1O_2^* + O_1^* O_2 = I_1+ I_2 + 2I_1I_2 \cos \delta \quad ....(6)$$

Where, I_1 and I_2 are the intensities of O_1 & O_2. The Phase Difference δ is given by:

$\delta = (K_2-K_1).L$ …… (7)

Where K_2 is the observation vector, K_1 is the illumination vector and L is the displacement vector. Thus the evaluation of the phase δ is gives the displacement. The fringes formed represent contours of constant displacement. The fringe formation in ESPI is well documented [10]. The intensity distributions $I_1(x,y)$ and $1_2(x,y)$ recorded before and after the object displacement respectively can be written as:

$I_l(x,y) = a_{12} +a_{22} + 2a_1a_2 \cos(\nwarrow)$ …..(8)

$I_2(x,y) = a_{12} +a_{22} + 2a_1a_2 \cos(\nwarrow \pm \Leftarrow)$ .....(9)

Where a_1 and a_2 are the amplitudes of the object and reference waves $\Leftarrow$ is the phase difference between them and φ is the additional phase change introduced due to the object movement.

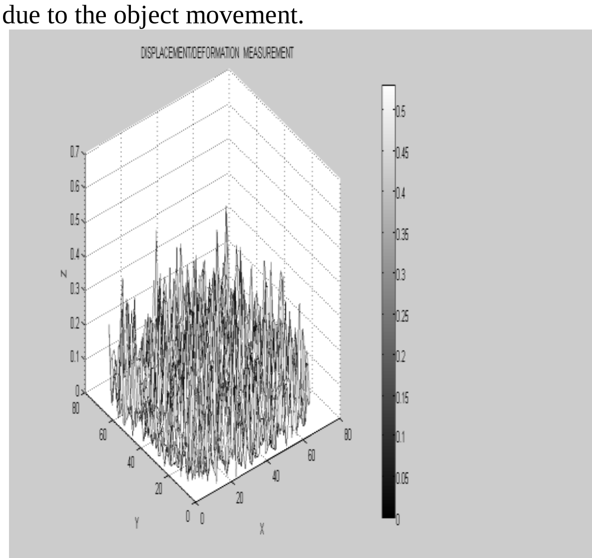

Figure 6. Deformation measurement

The subtracted signal as displayed on the monitor is given by:

$I_1 - I_2 = 4 |a_1a_2 \sin[\nwarrow + (\Leftarrow /2)] \sin (\Leftarrow /2)|$ ....(9)

Thus the brightness is modulated by a sine factor of the phase. The brightness on the monitor is maximum value when $\Leftarrow$ = (2m +1) p and zero when $\Leftarrow$ = 2mp, which produces a fringe pattern on the monitor. The phase change $\Leftarrow$ is the same as in holography. Electronic Speckle Pattern Interferometry is based on the coherent addition of the scattered light from the specimen surface and a reference laser beam [11] is a very good tool for optical metrology.

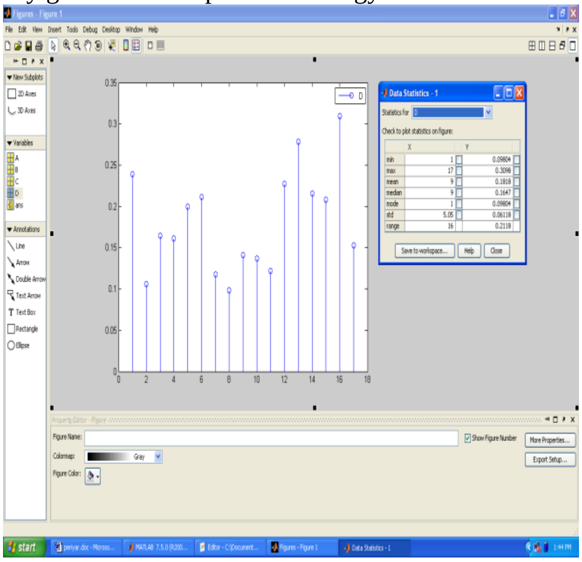

Figure 7. Measurement of displacement- Matlab

III. Conclusion

This paper shows recent developments and applications of digital image correlation in optical metrology. The results are well agreed with the other conventional methods like strain gauge. A low cost experimental platform was set up based on Michelson Interferometer using aluminum plate as a specimen and its deformation has been measured using image processing method.

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