Relative Error in Out-of-plane Measurement Due to the Object Illumination Type

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Abstract

In this work the sensitivity vector is analyzed for collimated and divergent illumination for an out-of-plane arrangement. The geometry of the optical setup that we used allowed us to find sensitivity mostly along the pulling direction; the other two components of the sensitivity vector were relatively small. We measured the displacement induced only along the pulling direction. Experimental and theoretical results are presented for the out-of-plane electronic speckle pattern interferometer. The analyzed object was an aluminum plate.

Introduction

Out-of-plane arrangements based on electronic speckle pattern interferometry (ESPI) allow investigating the mechanical behavior of an object subjected to stress. The technique comprises obtaining a phase map which is correlated with the sensitivity vector in pursuit of knowing the displacement map. According the setup, the sensitivity *vector* depends on both its geometry and of the type object illumination [1-3]. In this work it is presented an analysis of sensitivity vector when divergent or collimated light is used to illuminate the surface target.

A) Sensitivity vector for divergent illumination

The phase difference between the reflecting beam and the reference beam is indirectly recorded through intensity of an interference pattern named as a speckle interferogram. Alteration in the phase difference, $\Delta\phi$, before and after a mechanical loading is determined by the scalar product of the displacement vector, $\vec{d}$, and the sensitivity vector $\vec{e}$:

$$\Delta\phi = \vec{d}(P)\cdot\vec{e}(P), \quad (1) \qquad \text{where } \vec{e}(P) = \frac{2\pi}{\lambda}\left[\hat{b}(P) - \hat{s}(P)\right], \quad (2)$$

and $\hat{b}$ and $\hat{s}$ are observation and illumination unit vectors respectively.

$$\hat{b}(P) = \begin{pmatrix} b_x(P) \\ b_y(P) \\ b_z(P) \end{pmatrix} = \frac{1}{\sqrt{(x_b-x_p)^2+(y_b-y_p)^2+(z_b-z_p)^2}}\begin{pmatrix} x_b - x_p \\ y_b - y_p \\ z_b - z_p \end{pmatrix}, \quad (3)$$

$$\hat{s}(P) = \begin{pmatrix} s_x(P) \\ s_y(P) \\ s_z(P) \end{pmatrix} = \frac{1}{\sqrt{(x_p-x_s)^2+(y_p-y_s)^2+(z_p-z_s)^2}}\begin{pmatrix} x_p - x_s \\ y_p - y_s \\ z_p - z_s \end{pmatrix}. \quad (4)$$

$e_x \approx 0$; $e_y \approx 0$

$$\boxed{e_z = \frac{2\pi}{\lambda}\left[\frac{z_b - z_p}{\sqrt{(x_b-x_p)^2+(y_b-y_p)^2+(z_b-z_p)^2}} - \frac{z_p - z_s}{\sqrt{(x_p-x_s)^2+(y_p-y_s)^2+(z_p-z_s)^2}}\right]} \quad (5)$$

$$\boxed{\Delta\phi = e_z w} \quad (6)$$

Commonly, interferometric optical arrangements use collimated wavefronts for object surface illumination. In other cases, divergent illumination is used. For simplicity in both cases, it is considered that the interest component of the sensitivity vector e_z is constant. This approach introduces an error in the calculation of the displacement field.

B) Sensitivity vector for collimated illumination where e_z is assumed as constant

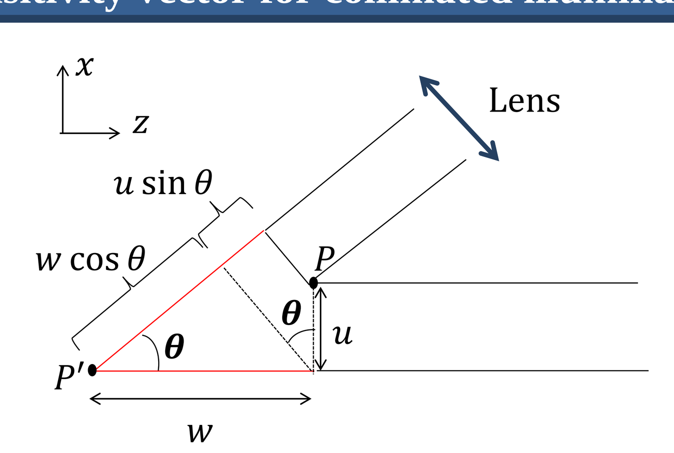


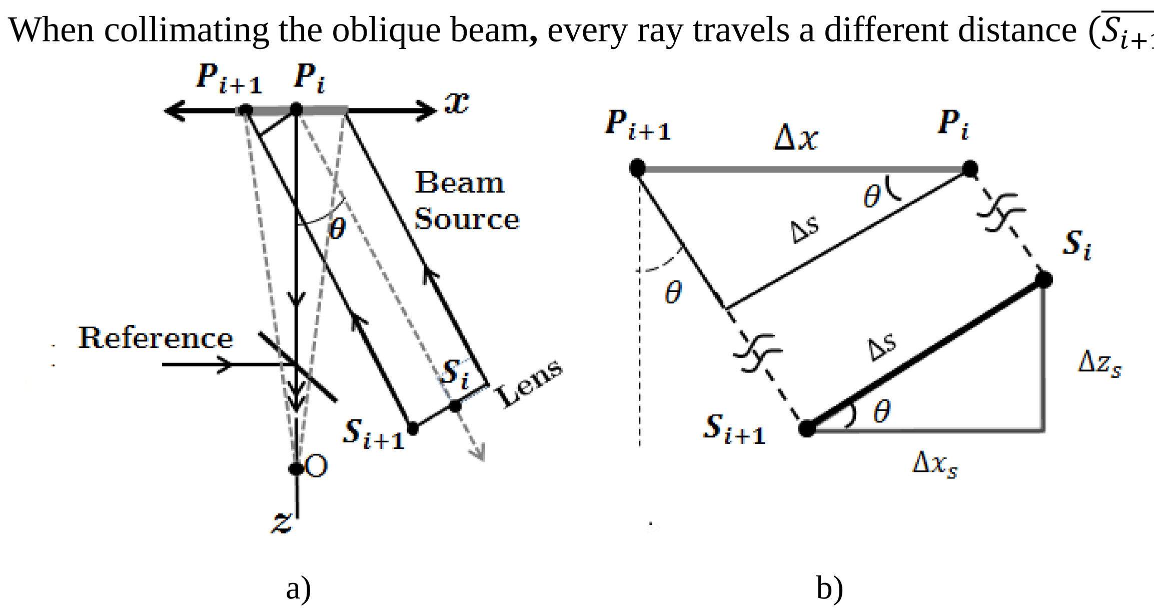
Fig. 1. Optical difference path using collimated beam

$$\Delta\phi = \frac{2\pi}{\lambda}\left[w(1+\cos\theta) + u\sin\theta\right] \quad (7)$$

$$\theta \approx 0 \rightarrow \boxed{e_z \approx \frac{2\pi}{\lambda}[2];} \qquad \boxed{\Delta\phi = \frac{4\pi}{\lambda}w}$$

C) Sensitivity vector for collimated illumination where e_z is calculated without approximation

When collimating the oblique beam, every ray travels a different distance ($\overline{S_{i+1}P_{i+1}} \neq \overline{S_iP_i}$).



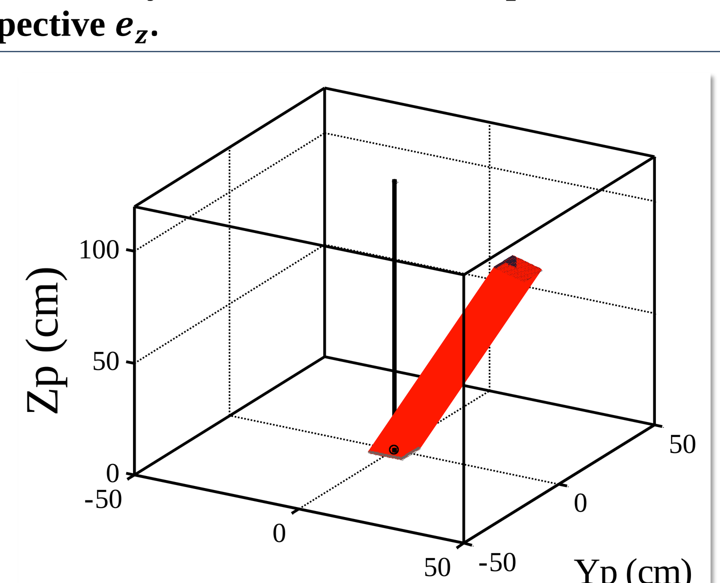
$$\Delta x = \frac{\Delta s}{\cos\theta} = \frac{\Delta x/_{\cos\theta}}{\cos\theta}$$

Fig. 2. a) Collimated and oblique illumination b) Geometry of oblique collimate beam

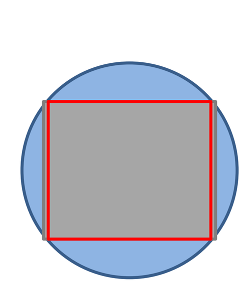
Expressions in order to obtain the rays coordinates at object plane according to the coordinates of rays coming out from the lens

$$\boxed{S_{i+1}\colon (x_s \mp \Delta s\cos\theta\,, y_s, z_s \pm \Delta s\sin\theta\,),} \qquad \boxed{P_{i+1}\colon \left(x \mp \frac{\Delta x_s}{\cos^2\theta}, y, 0\right)}$$

Then, the rays coordinates on lens plane can be calculated and evaluated in equation (5) in order to compute the respective e_z.



Lens: $S(37.46\ cm, 0,\ 92.78\ cm)$
Object: P(0, 0, 0)



Lens: $r = 2.5\ cm$
Object: $2\ cm \times 1.6\ cm$
Illuminated Zone: $1.89\ cm \times 1.6\ cm$

Fig. 3. Trace of rays between lens plane and object plane according to lens size.

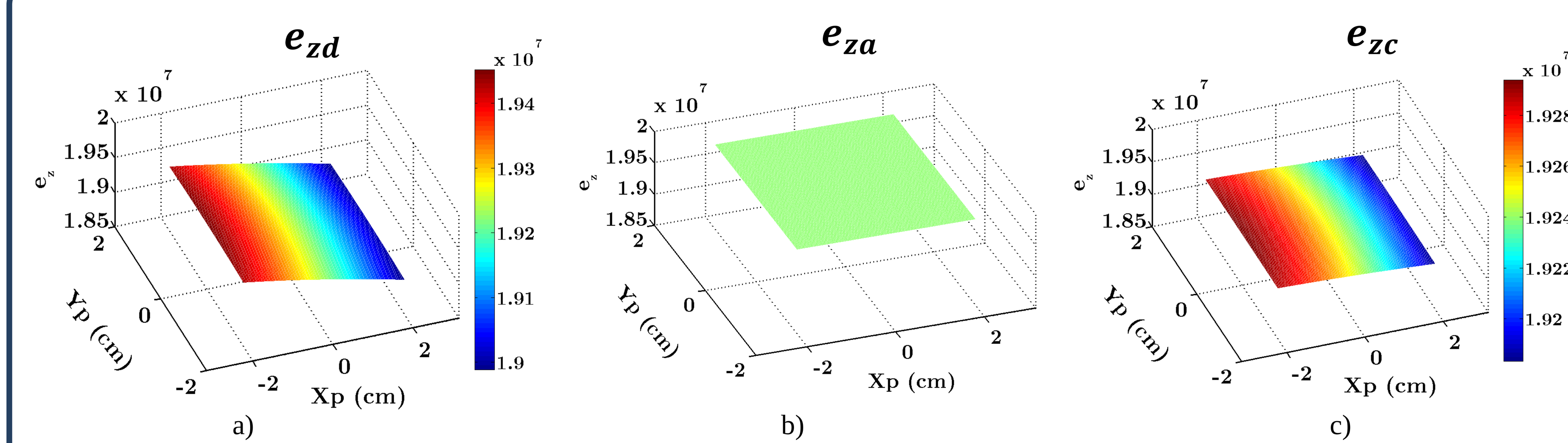


Fig. 4. Component e_z of the sensitivity vector for the cases: a) divergent illumination, b) assumed as constant, c) without approximation

$$E_{a-d} = 100 * \left|\frac{e_{za} - e_{zd}}{e_{zd}}\right|\ ;\ E_{max}: 5.24\% \qquad E_{a-c} = 100 * \left|\frac{e_{za} - e_{zc}}{e_{zc}}\right|\ ;\ E_{max}: 3.46\%$$

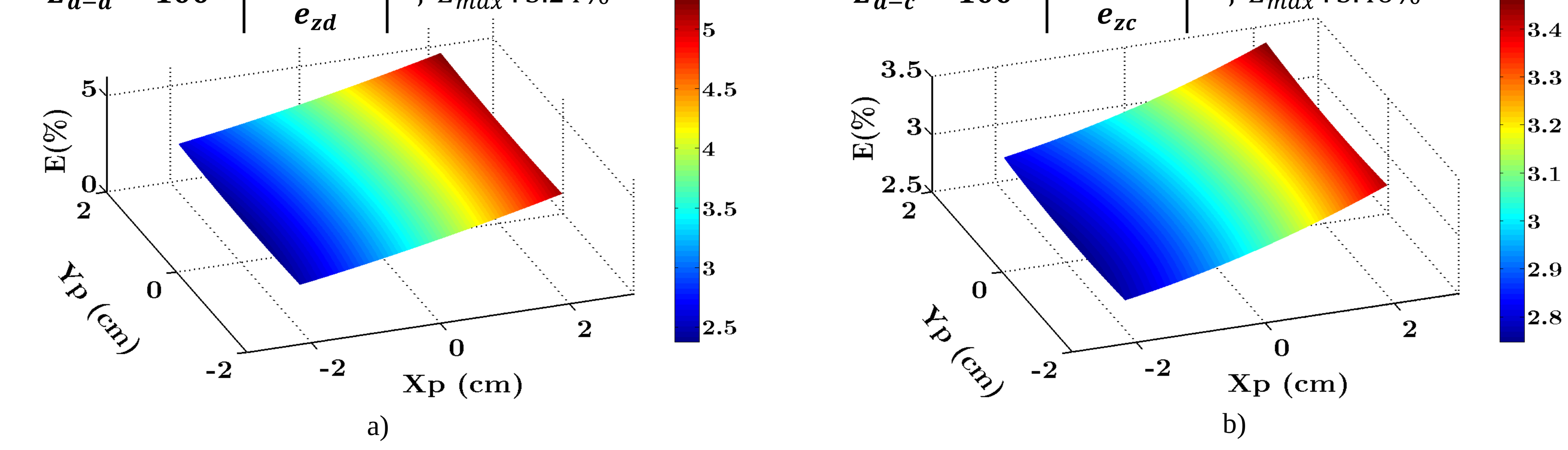


Fig. 5. Error map due to the assumption of that sensitivity vector component e_z is constant when is used: a) divergent illumination b) collimated light.

Experimental Results

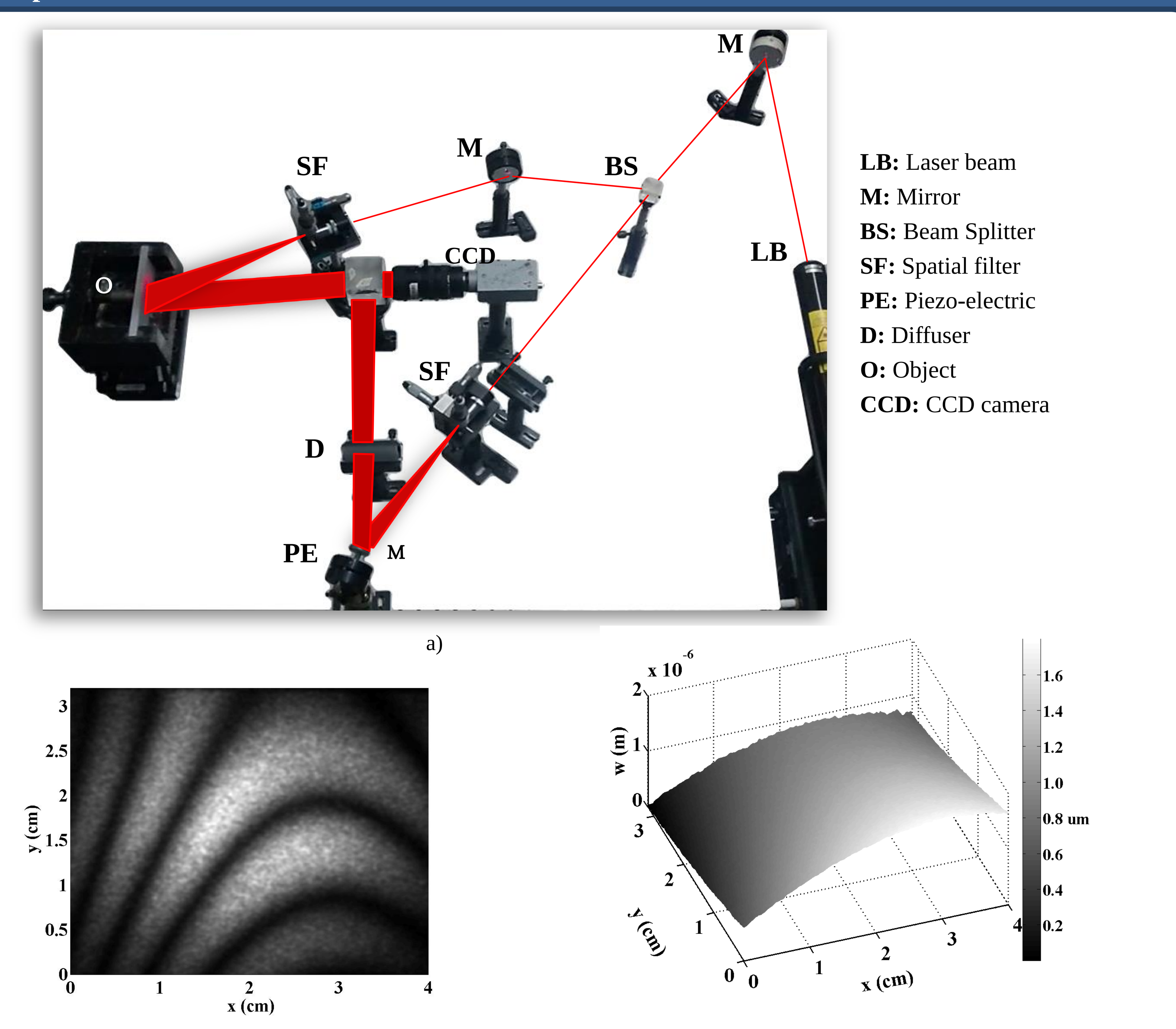


Fig. 6. a) Experimental setup – out-of-plane interferometer b) Obtained interferogram after applied load c) W displacement map

We have analyzed the use of object divergent and collimated illumination in out-of-plane speckle interferometry. The displacement field $w(x,y)$ and associated error to its measurement were evaluated when divergent illumination was used in the experiment and it is supposed that the sensitivity vector component e_z is constant. The analysis of the sensitivity vector variation due to spherical illumination is important in the stage of planning an interferometric measurement experiment to minimize the required displacement component error.

Acknowledgements

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References

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