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Experimental Assessment Of Compact Double-Aperture Four-Holographic-Lens Imaging System For In-Plane Displacements Measurement

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Abstract:
Coherent imaging systems employing two identical holographic lenses in a conjugate arrangement have demonstrated significant potential in speckle metrology, as they provide diffraction-limited imaging free from monochromatic aberrations. However, the minimum measurable in-plane displacement (measurement sensitivity) in such systems depends on the f-number of the holographic lenses. Since achieving a low f-number is constrained by the availability of high-quality pinholes only in limited sizes during holographic lens recording, the measurement sensitivity of two-holographic-lens imaging systems is limited. In this work, a compact double-aperture four-holographic-lens imaging system is investigated for in-plane displacement measurement. Experiments were performed using holographic lenses recorded at the same f-number (f/# = 7.4) but with different inter-beam recording angles of 9° and 18° between the plane and spherical recording beams. The experimental results demonstrate that, using holographic lenses recorded with the same f-number, a larger inter-beam recording angle yields higher measurement sensitivity. In contrast, the measurement sensitivity of the existing Duffy's imaging system and double-aperture two-hololens system is limited by the f-number of the lenses. Thus, by using a four-holographic-lens imaging system, the limitation imposed on the measurement sensitivity by the f-number of the holographic lenses can be overcome.

Keywords: *Holographic lenses, In-plane displacement, Speckle metrology, Coherent imaging, Diffractive optical elements*

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I. Introduction

Precise measurement of in-plane displacement is of fundamental importance in precision engineering, structural analysis, and advanced manufacturing. Laser speckle techniques are widely used in experimental mechanics to measure displacement and deformation in engineering structures. Since the pioneering work of Leendertz [1] and Archbold et al. [2-3], which demonstrated the use of laser speckles in in-plane displacement measurements, extensive research has been conducted in many laboratories, resulting in significant advancements in the speckle-based methods [4]. These techniques are generally categorized into speckle photography and speckle interferometry. These speckle-based measurement techniques have been widely employed for measuring in-plane displacements, out-of-plane tilts, in-plane rotations, vibrations, and non-destructive testing applications [5-8].

Holography has been established as a superior technique for fabricating lightweight, inexpensive optical elements such as gratings, lenses, mirrors, beam splitters, etc. [9]. A holographic lens is the hologram of a point source [10-11]. It can be recorded using the interference pattern of a coherent plane wave and a spherical wave [11]. High-resolution holographic films are used to record the interference pattern. When holographic lenses are reconstructed with a coherent beam of monochromatic light, they show focusing properties like conventional lenses. However, unlike their conventional counterparts, which work on the phenomenon of refraction, holographic lenses achieve their required function through the phenomenon of diffraction. Other than speckle metrology, recent works have shown the potential of holographic lenses in laser Doppler anemometry [12], optical fiber communication [13], head-up display [14], photovoltaic concentrators [15-17], and many other fields [18-21].

To measure in-plane displacements with high precision in speckle metrology, Shakher et al. [22] first demonstrated the use of a single holographic lens-based imaging system. However, in speckle metrology, one usually deals with an extended object, and a single holographic lens gives aberration-free imaging performance only for a single point, which is the source of the spherical wave during holographic lens recording [11]. Therefore, to obtain aberration-free imaging performance over an extended object field, Shakher [23-24] proposed a two-hololens coherent imaging system in speckle metrology. Shakher demonstrated that aberrations introduced by the first holographic lens for various points on the extended object are nullified by the second holographic lens.

For the direct measurement of in-plane displacement components, analogous to Duffy's imaging system [25], Jayaswal et al. developed low-cost double-aperture imaging systems with two identical holographic lenses with a twin-aperture mask, based on the aberration-correction principle of the two-hololens system [26]. In these double-aperture configurations [25-26], each speckle is modulated by a plane grating structure of period $\frac{\lambda}{2\sin\phi}$ due to the interference of two speckle fields coming from the apertures. Consequently, the minimum measurable in-plane displacement, i.e., the measurement sensitivity (σ) of the double-aperture systems is given by $\sigma = \frac{\lambda}{2\sin\phi}$, where ϕ is the semi-angle subtended by each aperture at the image plane. For a lens of diameter D and focal length f, $sin\phi = \frac{D}{2f} = \lambda\,(f/\#)$, when using the entire lens aperture [26]. Accordingly, the minimum measurable in-plane displacement using conventional Duffy's system [24] and double-aperture two-hololens system [26] is limited to $\sigma = \lambda\,(f/\#)$. Therefore, improving the measurement sensitivity requires holographic lenses with a lower f-number.

In practice, however, reducing the f-number of a holographic lens is constrained by the recording process. Since high-quality pinholes are available only in finite sizes, the minimum achievable f-number is limited by the diameter of the pinhole used to generate the spherical recording beam. For a pinhole of diameter (d), the lowest attainable f-number $\frac{d}{2.44\,\lambda}$ [12, 27]. Consequently, the measurement sensitivity of the double-aperture two-hololens systems is fundamentally limited by the minimum achievable f-number of the holographic lenses.

To determine whether the practical limitation imposed by the f-number of holographic lenses on measuring minimum in-plane displacement can be overcome without employing low f-number holographic lenses, a compact four-hololens imaging system has been experimentally investigated using holographic lenses recorded with the same f-number but with different inter-beam recording angles. Experiments were carried out using holographic lenses recorded with a typical f-number of 7.4, diameter 24 mm, focal length 178 mm, and inter-beam recording angles of 9° and 18° between the plane and spherical recording beams. The performance of these holographic lenses in the four-hololens configurations was comparatively evaluated in terms of the minimum measurable in-plane displacement (measurement sensitivity). The experimental results demonstrate that, when holographic lenses recorded with the same f-number are used in a four-hololens system, lenses recorded with a large inter-beam recording angle can measure smaller in-plane displacements in comparison to those holographic lenses recorded with a smaller inter-beam recording angle. Thus, the practical limitation associated with the f-number on measurement sensitivity can be overcome by using holographic lenses recorded with a large inter-beam recording angle in a double-aperture four-hololens system.

II. Experimental

Lens Recording

All the holographic lenses used in this work were recorded by interfering spherical beams originating from a point source (pinhole) and plane beams of laser light on high-resolution holographic plates. To obtain on-axis imaging performance, the plane beam was incident normally on the recording plane, and the spherical beam was incident obliquely at an angle ϕ with respect to the normal to the recording plane, as shown in Fig. 1. For experimental analysis, holographic lenses were recorded with ϕ = 9° and ϕ = 18°. A 12 mW He-Ne laser (M/S Newport USA) operating at a wavelength of 0.6328 μm was used to generate both the spherical and plane beams. During recording, a 5 μm diameter pinhole (M/S Newport USA), which was the point source for generating the spherical beam, was positioned at a distance of 178 mm from the recording plane. Consequently, the recorded holographic lenses had a focal length of 178 mm. Using a pinhole of diameter (d = 5 μm) and a recording wavelength (λ = 0.6328 μm), the lowest attainable f-number is given by (f/#) $\frac{d}{2.44\,\lambda} = 3.24$ [12, 27]. From the relation $f/\# = \frac{f}{D}$, where f is the focal length, and D is the lens diameter, the corresponding maximum attainable lens diameter for a holographic lens of focal length 178 mm is approximately 54 mm. However, using an appropriate aperture, the diameter of the recorded lenses was kept at 25 mm. High-resolution PFG-01 silver halide holographic plates [28] were used to record holographic lenses. After proper exposure to the PFG-01 plates, they were developed using the standard procedure [29-30].

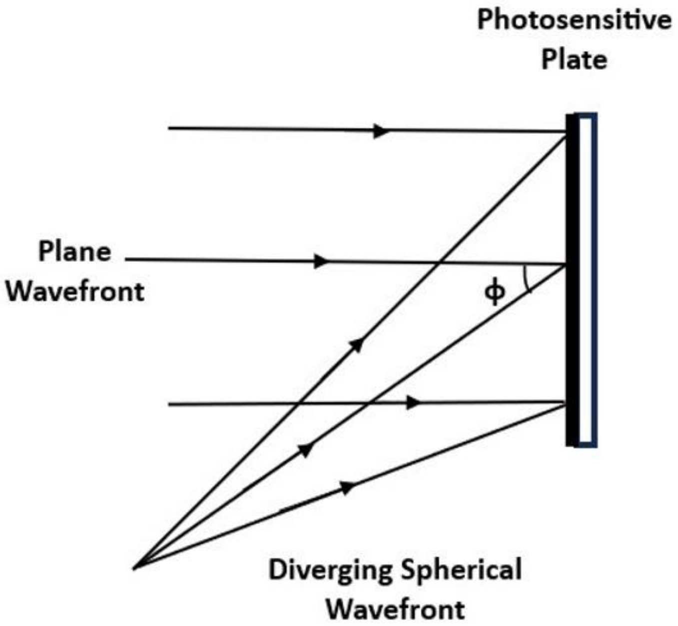

Fig.1 Simplified holographic lens recording geometries using plane and spherical wavefronts.

In-plane displacements measurement using compact double-aperture four-hololens coherent imaging systems

Fig. 2 illustrates the schematic of the experimental configuration employed for in-plane displacement measurement using the double-aperture four-holographic-lens systems. Holographic lenses recorded with an identical f-number (f/# = 7.4) and different inter-beam recording angles of 9° and 18° were employed in the imaging system. An expanded and spatially filtered laser beam with a wavelength of λ = 0.6328 µm was incident on an optical diffuser plate mounted on a linear translation stage. The diverging speckle field emerging from the diffuser was directed onto the holographic lens system, which formed an image of the diffuser plate containing the speckle pattern generated by the diffuser.

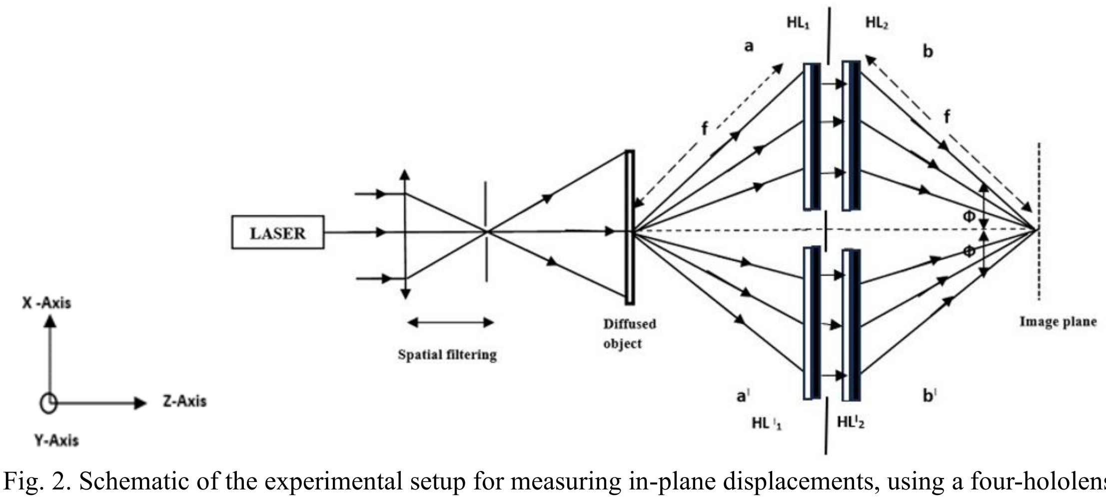

Fig. 2. Schematic of the experimental setup for measuring in-plane displacements, using a four-hololens system.$\mathrm{HL_1}$, $\mathrm{HL_2}$, $\mathrm{HL'_1}$, $\mathrm{HL'_2}$ are identical holographic lenses, and f is the focal length of the holographic lenses.

Double-exposure technique [31] was employed for measuring in-plane displacements that were applied to an optical diffuser. Double-exposure specklegrams corresponding to the different in-plane displacement values were recorded on PFG-01 silver halide holographic plates. Silver halide recording materials possess high spatial resolution and wide dynamic range along with high sensitivity, which help in accurately recording the fine details of speckle patterns [28]. For each measurement, the first exposure was recorded with the object in its initial position. The object was then translated by a known in-plane displacement along the x-axis, parallel to the holographic lens plane (see Fig. 2), using a precision motion controller (XPS series, Newport make), and a second exposure was recorded on the same plate. The recorded double-exposure specklegrams were subsequently processed using the point-wise filtering technique to obtain the Young's fringe patterns for displacement analysis [31]. Schematic of the point-wise filtering method of doubly exposed specklegrams shown in Fig. 3.

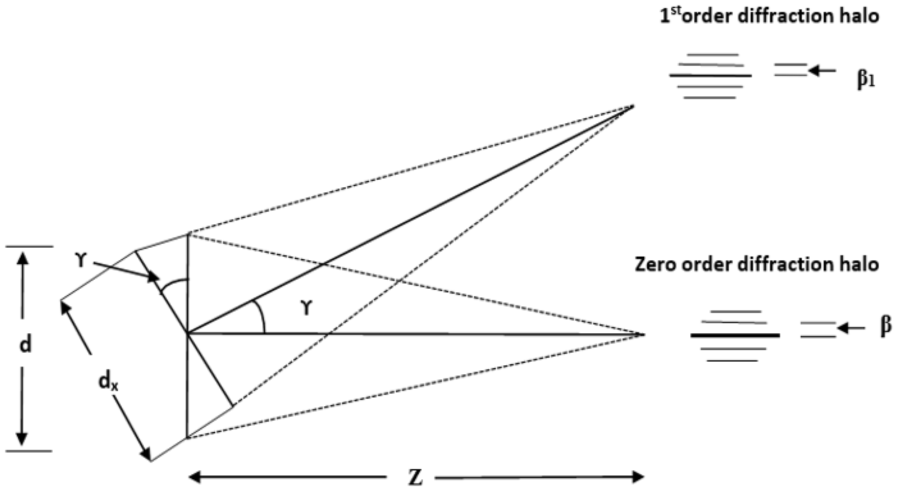

Fig. 3. Schematic illustrating fringe formation in ±1st order and zero-order (central) diffraction halo in the pointwise filtering method.

When an unexpanded laser beam is incident on the recorded specklegram, the double-aperture four-hololens imaging systems generate speckle correlation fringes in both the central (zero-order) and the first-order (±1) diffraction halos. However, due to the high visibility of correlation fringes in ±1st order, the width of fringes was measured in the ±1st order only using equation (1)

$$d = \frac{\lambda Z}{\beta_1 \cos \Upsilon} \quad (1)$$

In this equation, d denotes the applied in-plane displacement of the object point in a direction parallel to the plane of holographic lenses, λ is the wavelength of the illuminating light, Z is the distance between the recording medium and the observation plane, and β_1 represents the average fringe spacing, and ϒ is the angle between central zero-order and ± 1st order halos.

Several double exposure specklegrams were recorded to determine the minimum measurable in-plane displacements using holographic lenses (f/# = 7.4) and inter-beam recording angles of 9° and 18° in the imaging systems at a wavelength of λ = 0.6328 µm. Tables 1, and 2, present the measured in-plane displacements obtained using the holographic lenses recorded with inter-beam recording angles of 9° and 18°, respectively.

Table no 1: Measured in-plane displacements in first-order using holographic lenses with f/# 7.4 and inter-beam recording angle 9° in a four-hololens system (Fig. 2).

Applied In-plane displacement (in µm)	Measured In-plane displacement d_x (µm)	Distance between Specklegram and screen Z (cm)	Fringe spacing $\beta_1 \cos \Upsilon$ (mm)	Percentage error in the measurement
3	2.89	30	65.68	3.7
5	4.81	30	39.46	3.8
10	9.61	30	19.96	3.9
15	14.40	30	13.18	4.0
25	23.95	30	7.92	4.2
50	47.95	30	3.95	4.1

Table no 2: Measured in-plane displacements in first-order using holographic lenses with f/# 7.4 and inter-beam recording angle 18° in a four-hololens system (Fig. 2).

Applied In-plane displacement (in µm)	Measured In-plane displacement d_x (µm)	Distance between Specklegram and screen Z (cm)	Fringe spacing $\beta_1 \cos \Upsilon$ (mm)	Percentage error in the measurement
2	1.93	30	98.36	3.6
5	4.83	30	39.30	3.4
10	9.62	30	20.00	3.8
15	14.42	30	13.16	3.9
25	23.98	30	7.91	4.0
50	47.98	30	3.96	4.0

Fig. 4(a) and Fig.4(b) show diffraction halos containing Young's fringes in both the central (zero-order) and first-order halos, corresponding to the in-plane displacements of 2 µm, and 10 µm, obtained using the double-aperture four-hololens system using holographic lenses recorded with inter-beam recording angles of 18° between the plane and spherical recording beams in the four-hololens system, respectively.

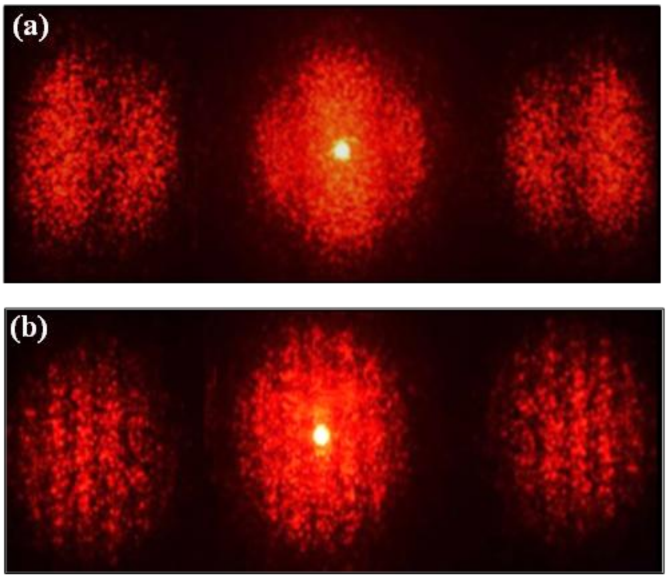

Fig. 4. Photographs of Young's fringes in ±1st order and zero-order (central) diffraction halo for the in-plane displacements of 2 µm, and 10 µm, obtained using the double-aperture four-hololens system using holographic lenses recorded with inter-beam recording angles of 18°.

III. Discussion And Conclusion

In this work, holographic lenses with a typical f-number of $f/\# = 7.4$, focal length of 178 mm, lens diameter of 24 mm, and inter-beam recording angles of 9° and 18° between the plane and spherical recording beams were employed in a double-aperture four-hololens system for the measurement of in-plane displacement. The corresponding experimental results are summarised in Tables 1, and 2, respectively. The performance of these configurations was comparatively evaluated in terms of their minimum measurable in-plane displacement (measurement sensitivity) for different inter-beam recording angles, keeping the same f/#.

Theoretically, the measurement sensitivity (σ) at wavelength λ for the existing double-aperture two-hololens system [26] is given by $\sigma = \lambda\,(f/\#)$ using holographic lenses of f-number (f/#). Accordingly, for holographic lenses with f/# = 7.4 operating at λ = 0.6328 µm, the minimum measurable in-plane displacement is 4.49 µm for the double-aperture two-hololens system. This limitation arises due to the limitations imposed by pinhole size on the minimum achievable f-number for holographic lenses.

Experimental results demonstrate that the minimum measurable in-plane displacement is 1.93 µm using holographic lenses recorded with inter-beam recording angles of 18° between plane and spherical recording beams in the four-holographic lens system. This represents an improvement of approximately 57% compared with the theoretical limit of 4.49 µm for the conventional double-aperture two-hololens system using holographic lenses of the same f-number of 7.4. Thus, using holographic lenses recorded with a typical f/# and high inter-beam recording angles in a four-holographic-lens imaging system, the limitation imposed by pinhole size on measurement can be avoided.

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