Experimental Analysis and Evaluation of Single Aperture and Double Aperture Compact Holographic Imaging Configurations for In-Plane Displacement Measurement in Speckle Metrology

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***Abstract*—In this work, a comparative experimental analysis of single-aperture and double-aperture compact holographic imaging systems to measure in-plane displacement components in speckle metrology has been presented. The single-aperture configuration uses two identical holographic lenses for speckle photography, while the double-aperture configuration employs four identical holographic lenses for speckle interferometry for diffraction-limited imaging performance almost free of all monochromatic aberrations. Further, to achieve on-axis imaging performance, holographic lenses have been recorded in different recording geometries for single-aperture and double-aperture configurations. Typically, in these imaging configurations, the holographic lenses are placed at a distance equal to the sum of their focal lengths, in accordance with Fourier theory. Experiments have been performed to demonstrate that the separation between the holographic lenses of the imaging systems has no marked effect on the measurement of in-plane displacement components. The results of measuring in-plane displacement components for both imaging configurations are presented. The obtained results approximately match the actual displacement applied between the two exposures. Based on the experiments, it is observed that a compact arrangement of holographic lenses in these configurations provides ease of experimentation, and problems arising due to system bulkiness and lens alignment can be resolved. Additionally, the probability of occurring aberrations due to the slight misalignment of holographic lenses can be avoided by using holographic lenses in a compact arrangement.**

***Index Terms*—Holographic Lens, In-plane Displacement, Speckle Photography.**

I. INTRODUCTION

Double exposure laser speckle photography technique is used to measure in-plane displacement components in speckle metrology [1-2]. The technique is most attractive due to its ease of experimentation where special surface finish and vibration isolation is not required contrary to holographic interferometry method. Further, the double exposure speckle photography method provides an additional benefit of obtaining whole-field displacement information in a single doubly-exposed specklegram [1-2]. In this technique, a rough surface is illuminated with a coherent beam of laser light, and image of the surface is recorded on a high-resolution photographic film using an imaging lens/ imaging systems corresponding to undeformed and deformed state of the object. When the recorded specklegram is probed by an unexpanded beam of laser light, two slightly displaced speckles corresponding to undeformed and deformed states behave as two scattering point sources of light and the light scattered from these points interfere among themselves to produce bright and dark speckle-correlation fringes. In-plane displacement occurred between the two states of the object can be measured by measuring the width of these fringes on a screen [1-3].

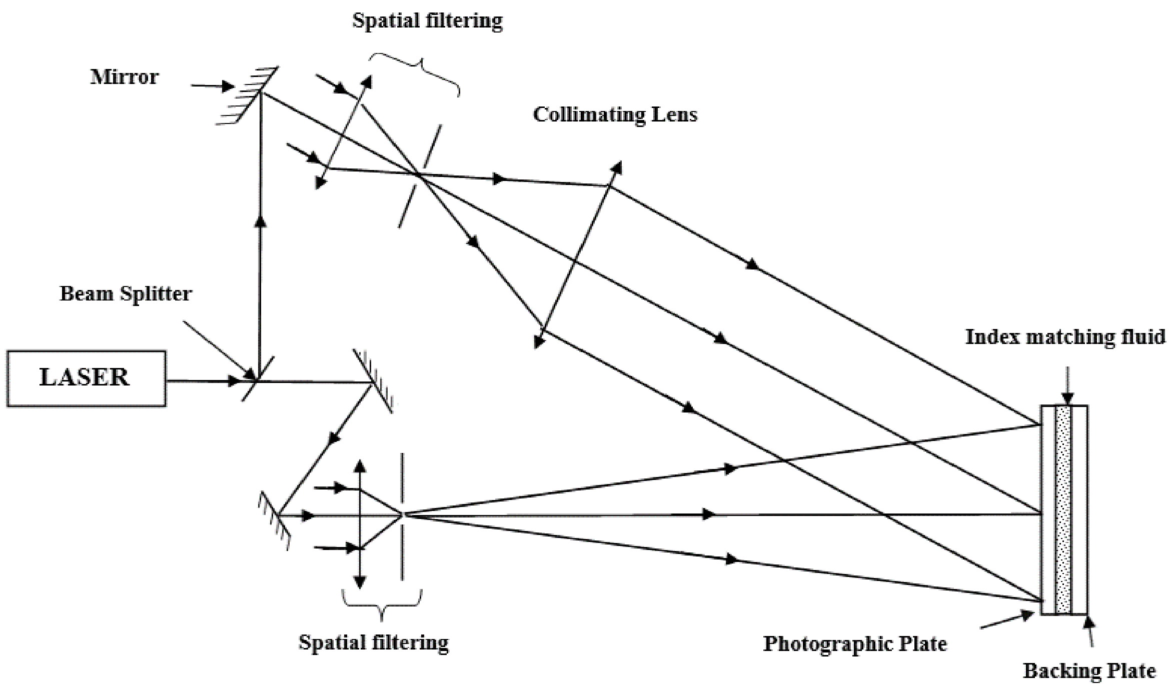
Archbold and Ennos [1-2] and Stetson [4] pointed out that in speckle photography, aberrations of the imaging lenses degrade the quality of speckle correlation fringes and reduces the accuracy of measurement by limiting the number of speckle correlation fringes and producing the curvature of the fringes. Earlier investigation performed by Chandra Shakher et al. [5-6] revealed that with appropriate design and playback conditions, holographic lenses can be used to obtain diffraction-limited imaging performance nearly free of all monochromatic aberrations in speckle metrology. A combination of two identical hololenses was utilized by Shakher et al [5-6] to get aberration free imaging performance over an extended object field in speckle metrology. The principle behind the working of two-hololens imaging system is that the second holographic lens of the imaging system nullifies the aberration produced by the first holographic lens in case of extended object imaging. Further, Shakher and Yadav [7] proposed a low f-number imaging configuration to increase sensitivity of measurements in speckle photography. The low f-number system was designed using two arms where each arm is a two-hololens system as proposed in reference [5-6]. Later Yadav et al. used the low f-number system in fracture mechanics to measure various fracture parameters [8]. However, alignment of holographic lenses in such imaging configuration is a difficult process. To align holographic lenses in such systems, one has to adjust variables that include two position coordinates and two angles of tilt per lens, and the rotation of lenses with respect to each other. In our recent publication [9], we have performed a detailed analysis of a four-hololens coherent imaging system for speckle metrology.

In the present work, to measure in-plane displacement component in speckle metrology, we present experimental analysis of a single aperture compact hololens imaging configurations for speckle photography and a double aperture compact hololens imaging configurations for speckle interferometry. To achieve on-axis imaging performance in the single-aperture hololens imaging configuration, holographic lenses were recorded using a spherical diverging wave originating from a point source and a mutually coherent plane wave such that the point source lies normally on the recording plane. Whereas for the double-aperture hololens imaging system, the spherical diverging wave is incident obliquely on the recording plane while recording the hololenses. A compact arrangement of holographic lenses was used in both the configurations to resolve the problems due to the bulkiness of the system and the alignment of the lenses. Experimental results for measuring typical in-plane displacements components using the single and double aperture configurations using compact holographic lenses are presented in Table 1 and Table 2, respectively. Using experiments, it is demonstrated that the separation between the holographic lenses in both the imaging configurations has no marked effect on the measurement.

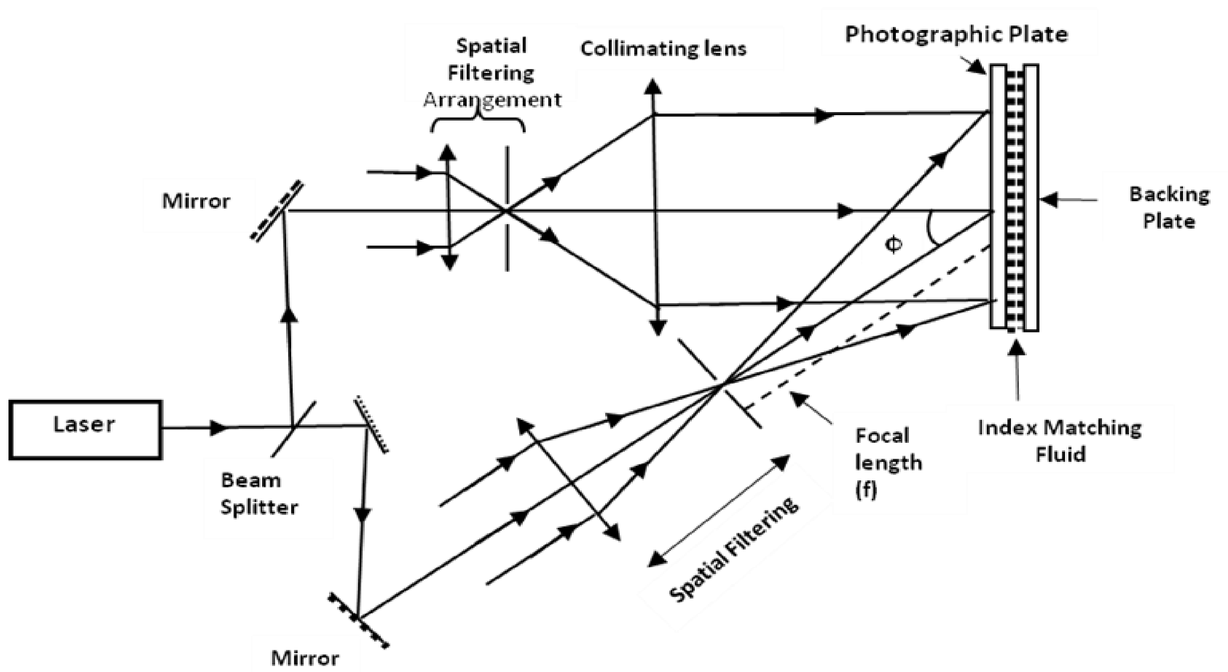
II. EXPERIMENTAL

2.1 Lens Recording and Playback Geometry

In order to reduce the effects of off-axis imagery in a single aperture configuration, holographic lenses were recorded on high-resolution photographic films in such a way that spherical waves originating from the pinhole fell normally on the recording plate. Whereas for a double aperture configuration, holographic lenses were recorded with plane waves falling normally on the recording plate to reduce the effect of off-axis imagery. Schematics of the recording geometry of holographic lenses for a single aperture and double aperture configurations are shown in Fig. 1 (a) and Fig. 1 (b), respectively. Fig. 2 (a) and Fig. 2 (b) show the schematic of imagery of an extended object for one-to-one imagery through a single aperture and double aperture configurations, respectively. In order to nullify the coefficients of monochromatic aberrations in imaging over an extended object field, it is necessary to use an arrangement of two identical holographic lenses for a single-aperture configuration and in each arm of a double-aperture configurations [5-6, 9].

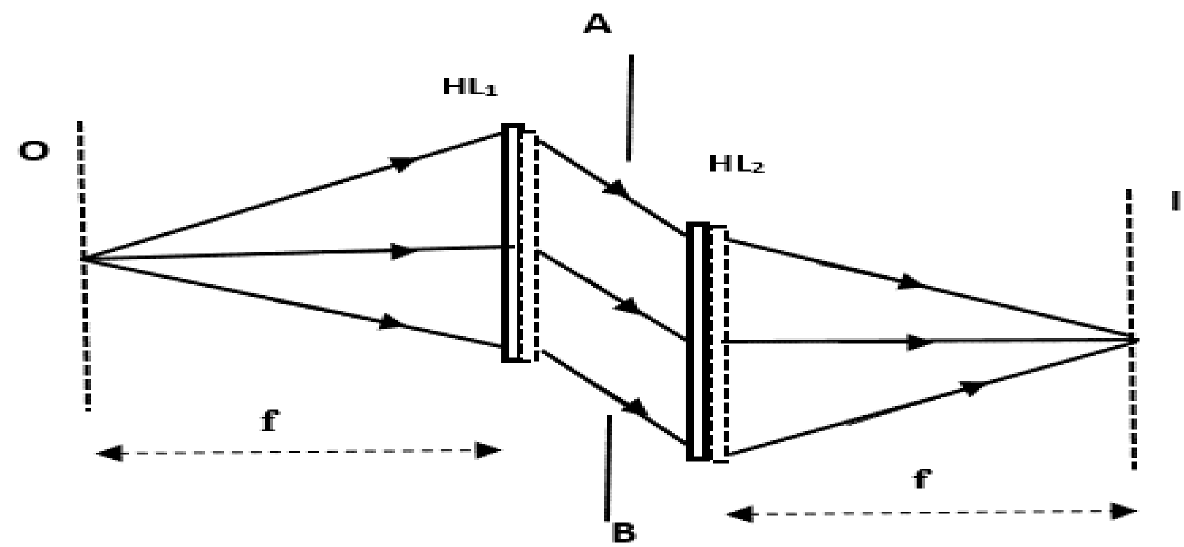


(a)

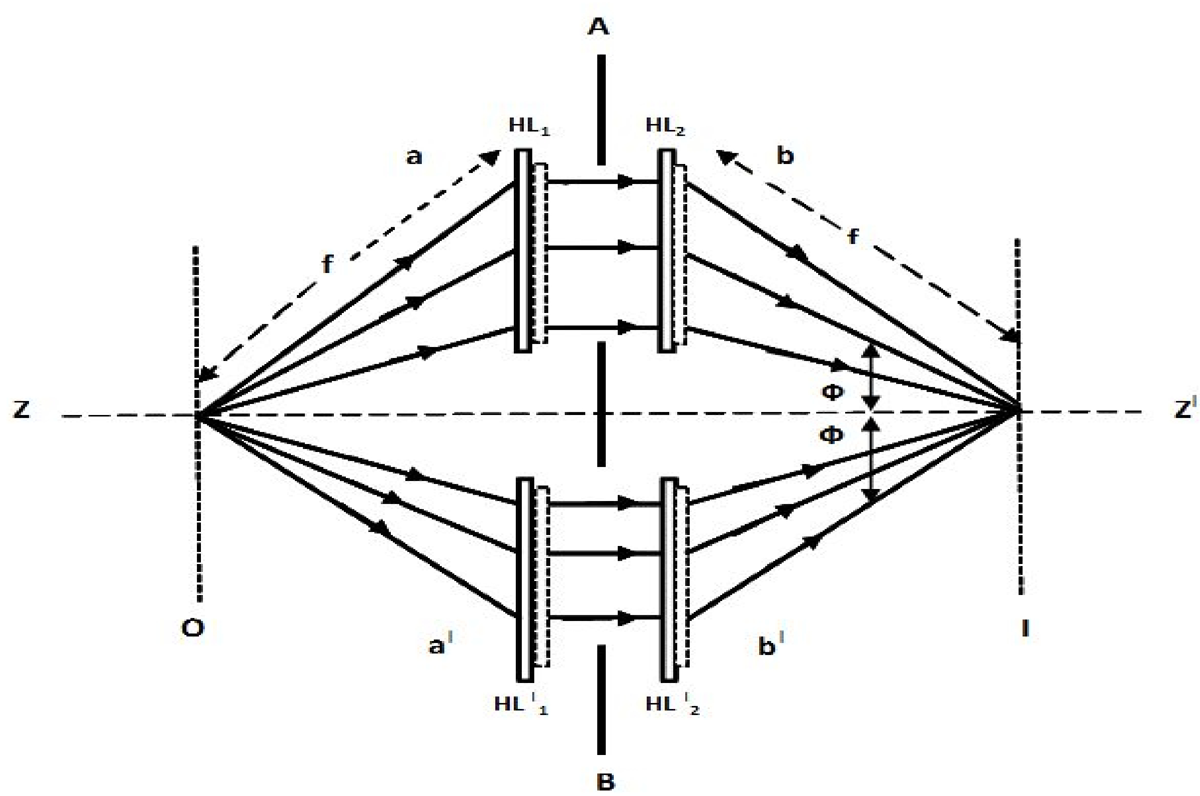


(b)

Fig. 1. Schematic of recording geometry of holographic lenses, (a) for single aperture configuration realized using a compact arrangement of two holographic lenses, (b) for double aperture configuration realized using a compact arrangement of four holographic lenses.



(a)



(b)

Fig. 2. Schematic of holographic imaging configurations, (a) for single aperture configuration realized using a compact arrangement of two holographic lenses (hololenses), (b) for double aperture configuration realized using a compact arrangement of four holographic lenses.

In Fig. 2, O is the object plane, I is the image plane, HL_1, HL_2, HL^{I}_1, HL^{I}_2 are holographic lenses. AB is an aperture stop, and f denotes the focal length of holographic lenses. For performing experiments, each holographic lens was recorded on high-resolution photographic plate (PFG-01 M/S Integraf) with typical value of focal length (f) = 180 mm and lens diameter = 24 mm. The angle ϕ between the plane and spherical wave in Fig. 2 (b) was chosen to be 18°. Recorded holographic lenses were developed using the standard procedure as given in reference [11].

2.2 Measurement of In-plane Displacement Components

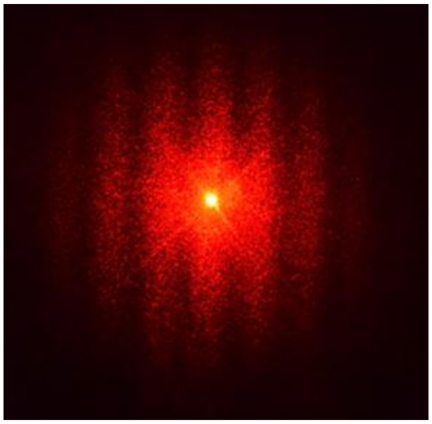
To measure in-plane displacements components, experiments were conducted using a two-hololens based single-aperture configuration and a four-hololens based double-aperture configuration. Hololenses in the imaging systems are kept close to each other to make the system compact. A diffuse object (optical diffuser) mounted on a linear translational stage was illuminated with an expanded beam of laser light and imaged through both imaging systems. Double exposure specklegrams corresponding to the different values of in-plane displacement were recorded. Point-wise filtering technique is used to measure width of the speckle correlation fringes [3]. Experimental results using two-hololens single-aperture configuration and a four-hololens double-aperture configuration are presented in Table 1 and Table 2, respectively. Single aperture configuration produces speckle correlation fringes only in zero-order diffraction halo as shown in Figure 3 (a), whereas double-aperture four-hololens system produces speckle correlation fringes in first-order and zero-order diffraction halos due to coherent superimposition of the speckle fields originating from each aperture as shown in Figure 3 (b). This increases the sensitivity of measurement due to modulation of each speckle with grating-like structure [9-10].

Table 1. Measured values of in-plane displacement using two-hololens single aperture imaging system.

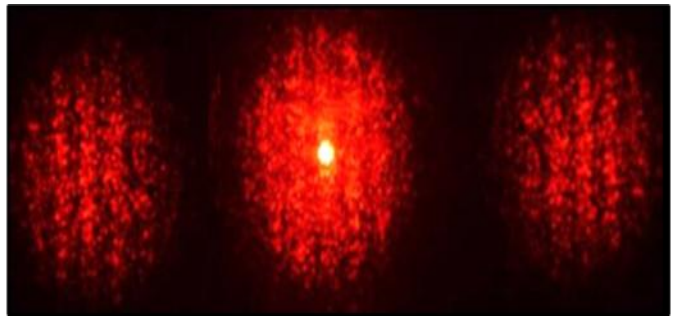
Actual In-plane displacement (μm)	Measured in-plane displacement (μm)	Error (in %)
5	4.63	7.4
10	9.24	7.6
25	23.15	7.4
70	64.90	7.3
100	92.70	7.3

Table 2. Measured values of in-plane displacement using four-hololens double aperture imaging system by examining the speckle correlation fringes in the first-order diffracted beam.

Actual In-plane displacement (μm)	Measured in-plane displacement (μm)	Error (in %)
4	3.88	3.0
10	9.72	2.8
25	24.25	3.0
70	68.12	2.7
100	97.28	2.7



(a)



(b)

Fig. 3. Speckle correlation fringes of Young's fringes types obtained using pointwise filtering of the double-exposure specklegrams recorded for 40 µm of in-plane displacement, (a) using the single-aperture hololens imaging system on the experimental setup shown in Fig. 2 (a), and (b) using the double-aperture hololens imaging system on the experimental setup shown in Fig. 2 (b).

III. DISCUSSION AND CONCLUSION

Table 1 and Table 2 present the comparative study between the actual value of object's in-plane displacements as recorded by the linear translational stage and corresponding values of displacements determined by analyzing speckle correlation fringes obtained by pointwise filtering of the double exposure specklegrams. For both imaging configurations, holographic lenses were recorded with equal values of focal length, lens diameter, and inter-beam recording angle between the plane and spherical waves. The F-number (F#) of the recorded lens is nearly equal to 7.5. The sensitivity of measurement of a single aperture configuration is determined by the average speckle size [3, 5-6]. For one-to-one imaging, the size of the speckle corresponds to a single aperture two-hololens system is 1.2 λ F#. In a double-aperture configuration, each speckle is modulated by a grid-like structure. The sensitivity of measurement for the double-aperture configuration is equal to the pitch of the grid, which comes out to be $\lambda/2 \sin\phi$ [3,7,9-10]. Where λ is the wavelength and ϕ is the inter-beam recording angle between the plane and spherical beams. While performing experiments, hololenses in these imaging systems were kept close to each other to make the system compact.

Experimental results presented in Tables 1 and 2 show that the compact arrangement of holographic lenses in the single-aperture two-hololens coherent imaging system and the double-aperture four-hololens coherent imaging system has no marked effect on the measurement of in-plane displacement components. Further, it can be seen that using identical holographic lenses in the double aperture configuration, measurement sensitivity can be enhanced.

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