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Experimental Assessment of a Compact Four-Hololens Imaging System Using Holographic Lenses from Glass and Emulsion Sides for In-Plane Displacement Measurement

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***Abstract*— *To achieve diffraction-limited imaging over extended objects with negligible monochromatic aberrations, coherent imaging systems based on two identical holographic lenses in a conjugate arrangement have gained considerable attention in speckle metrology. However, the measurement sensitivity, defined as the minimum measurable in-plane displacement of a two-hololens system, is limited by the f-number of the holographic lenses. To overcome the dependency of measurement sensitivity on f-number of holographic lenses, the use of a double-aperture four-hololens system is investigated. Holographic lenses are employed from both emulsion and glass sides in the four-hololens system. Experiments were performed using holographic lenses recorded with a typical f-number of 7.1 and inter-beam recording angles of 11° and 18° between the plane and spherical recording beams. The experimental results demonstrate that holographic lenses recorded with a larger inter-beam recording angle provide high measurement sensitivity, while the use of holographic lenses from emulsion and glass sides has no significant effect on the in-plane displacement measurement. Furthermore, employing holographic lenses on both the emulsion and glass sides facilitates the easy alignment of the holographic lenses within the four-hololens system.*

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 is a well-established technique for fabricating lightweight and low-cost optical elements, including gratings, lenses, mirrors, and beam splitters [9]. A holographic lens, which is the hologram of a point source [10–11], is recorded by the interference of a coherent plane wave and a spherical wave on a high-resolution holographic film [11]. When reconstructed with coherent monochromatic light, it exhibits focusing properties similar to a conventional lens but operates through diffraction rather than refraction. Beyond speckle metrology, holographic lenses have found recent applications in laser Doppler anemometry [12], optical fiber communication [13], head-up displays [14], photovoltaic concentrators [15–16], and other optical systems [17–20].

To measure in-plane displacements with high precision in speckle metrology, Shakher et al. [21] 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 [22-23] 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 [24], 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 [25]. In these double-aperture configurations [24-25], 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 system, 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 [25]. Accordingly, the minimum measurable in-plane displacement using conventional Duffy's system [24] and double-aperture two-hololens system [25] 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, 26]. Consequently, the measurement sensitivity of the double-aperture two-hololens systems is fundamentally limited by the minimum achievable f-number of the holographic lenses.

This work investigates a double-aperture four-hololens imaging system for in-plane displacement in speckle metrology. Holographic lenses were employed from both the emulsion and glass sides in the four-hololens configuration. In-plane displacements were measured using holographic lenses recorded with a f-number of 7.1 and typical inter-beam recording angles of 11° and 18°. The experimental results demonstrate that holographic lenses recorded with a larger inter-beam recording angle enable the measurement of smaller in-plane displacements at the same f-number compared with holographic lenses recorded with a smaller inter-beam recording angle. Furthermore, the results show that using holographic lenses from either the emulsion or the glass side has no significant influence on the measured in-plane displacement. In addition, the use of holographic lenses from both the emulsion and glass sides simplifies the alignment procedure of the lenses in the four-hololens system.

II. EXPERIMENTAL

2.1 Recording of Holographic Lenses

In order to achieve on-axis imaging performance in the four-hololens system, holographic lenses were recorded with mutually coherent plane and spherical beams of laser light. While recording, 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 typical values of ϕ = 11° 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, 26]. 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 [27] were used to record holographic lenses. After proper exposure to the PFG-01 plates, they were developed using the standard procedure [28-29].

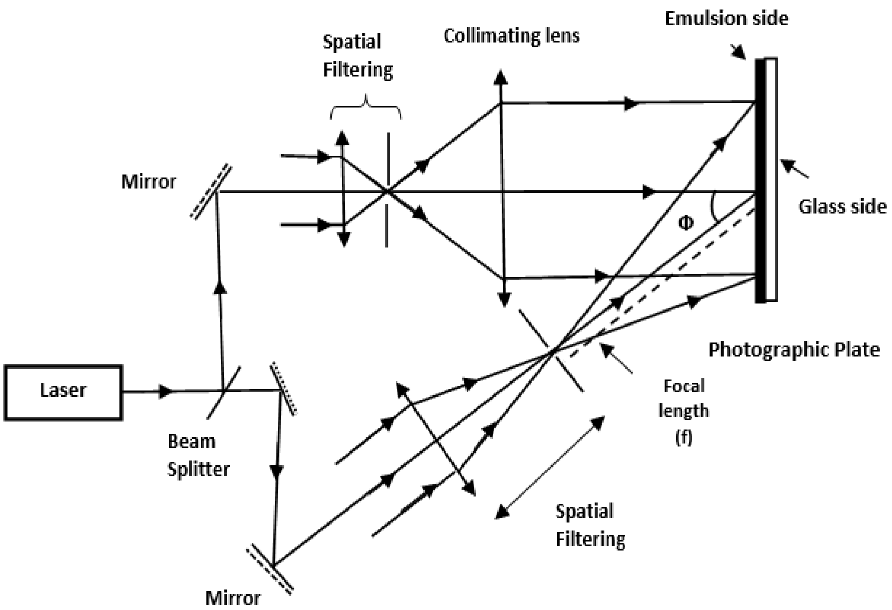

Fig. 1: Holographic lens recording geometries using plane and spherical wavefronts.

2.2 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-hololens systems with holographic lenses from glass and emulsion sides. Holographic lenses recorded with an identical f-number (f/# = 7.1) and different inter-beam recording angles of 11° and 18° were employed in the imaging system. An expanded and spatially filtered laser beam with a wavelength of $\lambda = 0.6328$ 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.

Double-exposure technique [30] 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 [27]. 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 [30]. Schematic of the point-wise filtering method of doubly exposed specklegrams shown in Fig. 3.

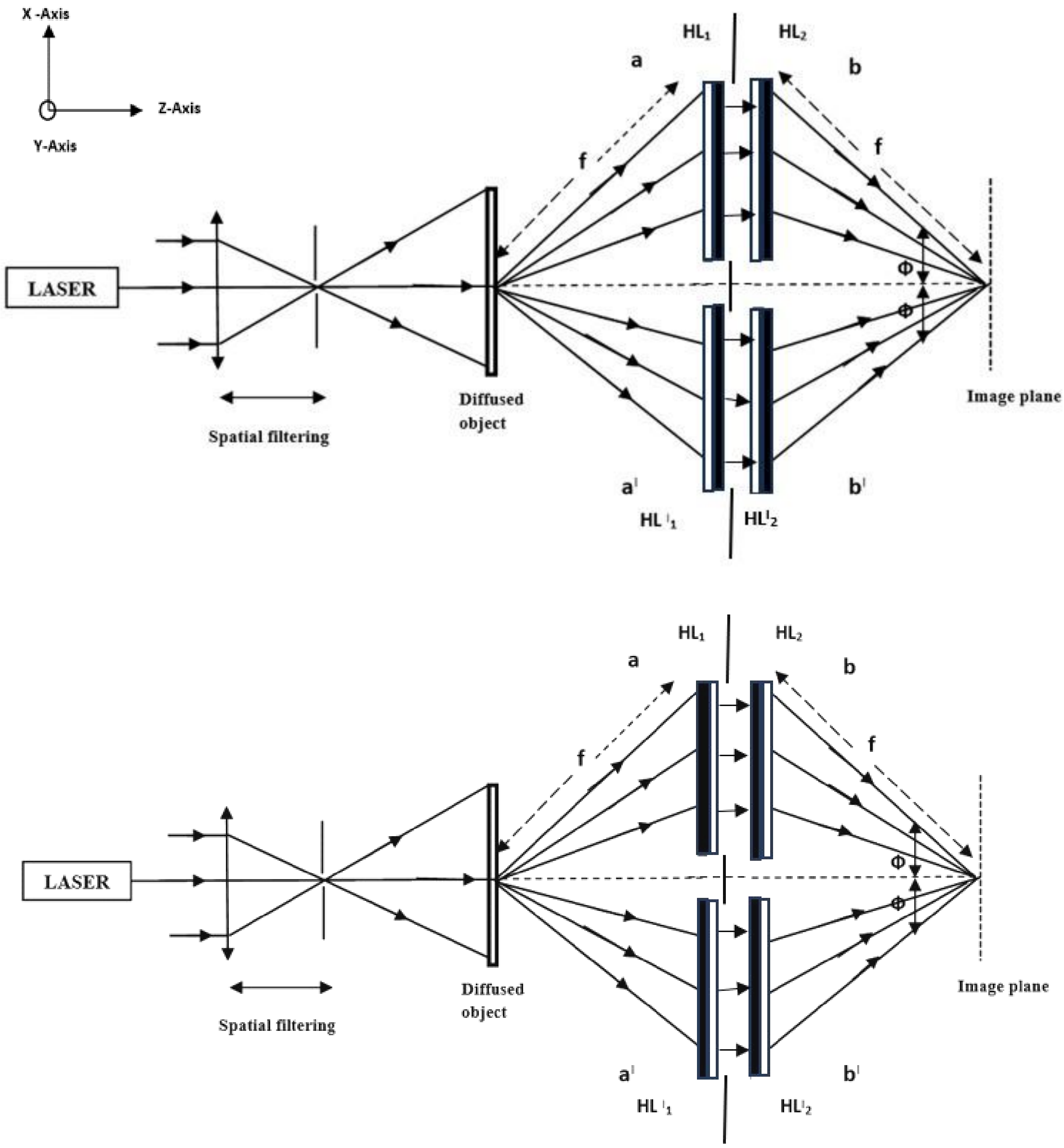

Fig. 2: Schematic of the experimental setup for measuring in-plane displacements using the four-hololens imaging system, Top: using holographic lenses from glass sides, Bottom: using holographic lenses from emulsion sides. HL_1, HL_2 , $HL^{\prime}_1$, $HL^{\prime}_2$ *are identical holographic lenses, f is the focal length, and ϕ is the inter-beam recording angle between the plane and spherical recording beams.*

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 $\pm 1^{st}$ order [26], the width of fringes was measured in the $\pm 1^{st}$ order only using equation (1)

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

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 laser 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/# = 7.1) and inter-beam recording angles of 11° and 18° in the imaging systems at a wavelength of λ = 0.6328 µm. Table 1 present the measured in-plane displacements obtained using the holographic lenses recorded with inter-beam recording angles of 11° and used from glass sides. Tables 2 and 3 present the measured in-plane displacements obtained using the double-aperture four-hololens system with holographic lenses recorded with inter-beam recording angles of 18° and used from glass and emulsion sides, respectively.

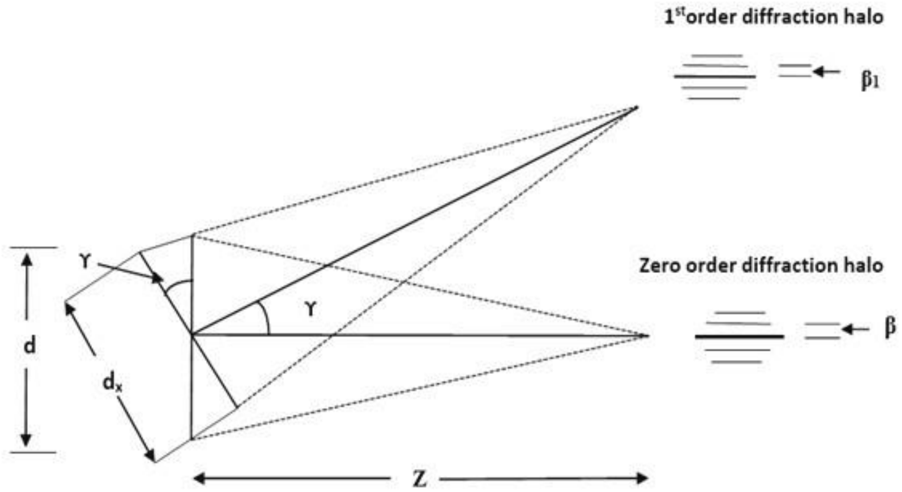

Fig. 3. Schematic illustrating fringe formation in ±1st order and zero-order (central) diffraction halo in the pointwise filtering method.

Table. 1: Measured in-plane displacements in first-order using holographic lenses from glass sides with f/# 7.1 and inter-beam recording angle 11° in a four-hololens system.

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	2.88	30	65.92	4.0
5	4.79	30	39.63	4.2
10	9.61	30	19.96	3.9
15	14.40	30	13.18	4.0
25	23.98	30	7.92	4.1

Table. 2: Measured in-plane displacements in first-order using holographic lenses from glass sides with f/# 7.1 and inter-beam recording angle 18° in a four-hololens system.

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	1.92	30	98.88	4.1
5	4.82	30	39.38	3.7
10	9.62	30	19.73	3.8
15	14.42	30	13.17	3.9
25	23.95	30	7.93	4.2

Table. 3: Measured in-plane displacements in first-order using holographic lenses from emulsion sides with f/# 7.1 and inter-beam recording angle 18° in a four-hololens system.

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	1.91	30	99.39	4.4
5	4.80	30	39.55	4.0
10	9.59	30	19.80	4.1
15	14.40	30	13.18	4.0
25	23.90	30	7.94	4.4

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 and used from the glass sides in the four-hololens system. Whereas Fig. 5(a) and Fig. 5 (b) show Young's fringes in both the central (zero-order) and first-order halos, corresponding to the same in-plane displacements of 2 µm and 10 µm, using the same holographic lenses from the emulsion sides in the four-hololens system.

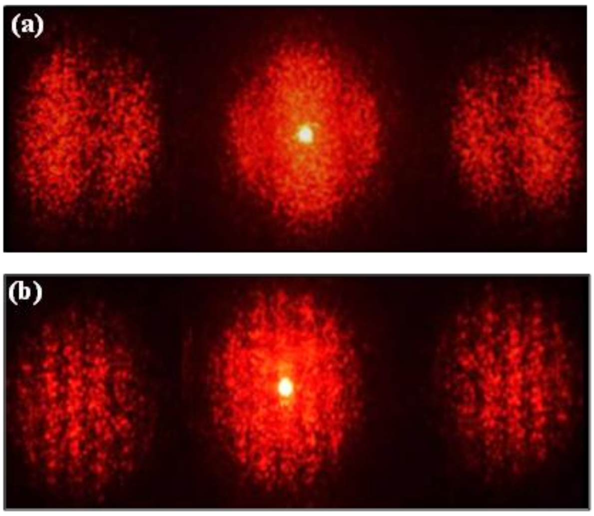

Fig. 4: Photographs of Young's fringes in ±1st order and zero-order (central) diffraction halo for the in-plane displacements of 2 µm and 10 µm, obtained using the double-aperture four-hololens system with holographic lenses recorded with inter-beam recording angles of 18° and used from glass sides.

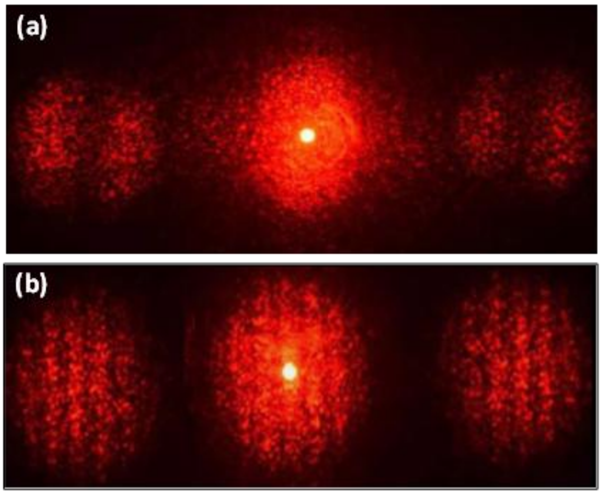

Fig. 5: Photographs of Young's fringes in ±1st order and zero-order (central) diffraction halo for the in-plane displacements of 2 µm and 10 µm, obtained using the double-aperture four-hololens system with holographic lenses recorded with inter-beam recording angles of 18° and used from emulsion sides.

III. RESULTS AND DISCUSSIONS

In this work, holographic lenses with a typical f-number of $f/\# = 7.1$, focal length of 178 mm, lens diameter of 24 mm, and inter-beam recording angles of 11° 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 holographic lenses were used from both emulsion and glass sides in the four-hololens system. The corresponding experimental results are summarised in Tables 1, 2, and 3, 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 same f/#.

Theoretically, the measurement sensitivity (σ) at wavelength λ for the existing two-hololens system [22-23, 25] is limited by f-number (f/#) of holographic lenses. This limitation arises due to the limitations imposed by pinhole size on the minimum achievable f-number for holographic lenses [26]. Using a holographic lens of f-number 7.1, the minimum measurable in-plane displacement is 4.49 µm at wavelength λ = 0.6328 µm using the two-hololens system.

Experimental results presented in this work demonstrate that the minimum measurable in-plane displacements were 2.88 µm and 1.92 µm using holographic lenses recorded with inter-beam recording angles of 11° and 18°, respectively, between the plane and spherical recording beams in the four-holographic lens system. This represents an improvement of approximately 36% and 57%, respectively, over the theoretical limit of 4.49 µm for the conventional two-hololens system employing holographic lenses with the same f-number of 7.1. These results indicate that using holographic lenses recorded with a typical f/# and high inter-beam recording angles in a four-hololens imaging system, the limitation imposed by f-number of holographic lenses on minimum measurable in-plane displacements can be avoided. Further, the experimental results show that using holographic lenses from either the glass side or the emulsions side in the four-hololens system has no marked effect on the measurement sensitivity. This provides the ease of alignment of holographic lenses in the four-hololens system and make the system experimentally viable for the measurement of smaller in-plane displacements.

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REFERENCES

[1] Archbold, E., Burch, J. M., & Ennos, A. E. (1970). Recording of in-plane surface displacement by double-exposure speckle photography. Optica Acta, 17, 883–898.

[2] Archbold, E., & Ennos, A. E. (1972). Displacement measurement from double exposure laser photographs. Optica Acta, 19, 253–271.

[3] Leendertz, J. A. (1970). Interferometric displacement measurement on scattering surfaces utilizing speckle effect. Journal of Physics E: Scientific Instruments, 3(3), 214.

[4] Sirohi, R. S. (2016). Introduction to optical metrology. CRC Press.

[5] Jayaswal, R. K., Khan, A. A., & Yadav, H. L. (2025). An experimental method to minimize errors in the in-plane displacement measurements in laser speckle photography using a dual aperture compact hololens imaging system. Russian Journal of Nondestructive Testing, 61(11), 859–868.

[6] Khan, A. A., Yadav, H. L., & Jaiswal, R. K. (2023). Experimental method to enhance sensitivity and accuracy of measurements in measuring fracture parameters around the crack tip using compact hololens imaging system. Russian Journal of Nondestructive Testing, 59(6), 501–506.

[7] Khan, A. A., & Yadav, H. L. (2022). Analysis of double aperture hololens imaging system through simulation and experimentation for its application in speckle metrology. Optics and Lasers in Engineering, 152, Article 106979.

[8] Khan, A. A., & Yadav, H. L. (2023). Holographic lenses for the precision measurement of surface displacement in speckle metrology. In Proceedings of the International Conference on Innovations in Engineering and Technology (ICIET) (pp. 1–4).

[9] Kim, N., Piao, Y.-L., & Wu, H.-Y. (2017). Holographic optical elements and application. In Holographic materials and optical systems. InTech.

[10] Schwar, M. J. R., Pandya, T. P., & Weinberg, F. J. (1967). Point holograms as optical elements. Nature, 215(5098), 239–241.

[11] Richter, A. K., & Carlson, F. P. (1974). Holographically generated lens. Applied Optics, 13(12), 2924–2930.

[12] Khan, A. A., & Yadav, H. L. (2023). Design and analysis of holographic lens based optical system for laser Doppler anemometry. Optics and Laser Technology, 167, Article 109660.

[13] Singh, A. K., Yadav, A., Khan, A. A., Roy, S., & Yadav, H. L. (2022). Design and analysis of holographic optical elements for their use as couplers with appreciable efficiency at different optical transmission windows. Optik, 261, Article 169184.

[14] Wang, Y., Yang, T., Lyu, X., Cheng, D., & Wang, Y. (2024). Ultra-simplified and low-cost head-up display system enabled by freeform holographic element. Optics and Laser Technology, 178, Article 111253.

[15] Wu, H. Y., Shin, C. W., Kwon, K. C., Lee, K. Y., Gil, S. K., & Kim, N. (2024). Holographic solar concentrator with wide band using multi-wavelength transmission grating. Optik, 318, Article 172106.

[16] Khan, A. A., & Yadav, H. L. (2023). Recording and analysis of off-axis multiplexed volume holographic lens for wavelength selective wide acceptance angle operation in concentrator photovoltaics. Optical Engineering, 62(8), Article 085103.

[17] Edwards, M. R., et al. (2022). Holographic plasma lenses. Physical Review Letters, 128(6), Article 065003.

[18] Nedelchev, L., et al. (2023). In-line and off-axis polarization-selective holographic lenses recorded in azopolymer thin films via polarization holography and polarization multiplexing. Applied Optics, 62, D1–D7.

[19] Hsieh, M. L., Chen, Z. F., Lin, S. H., & Lin, S. Y. (2025). An efficient and wide angle coupling of light to a thin film holographic optical element. Scientific Reports, 15(1), Article 23419.

[20] Khan, A. A. (2024). Uses of holographic lenses in interferometry and dispersive concentrating system for photovoltaics (Doctoral dissertation, National Institute of Technology Jamshedpur, India).
[21] Shakher, C., & Rao, G. V. (1984). Speckle metrology using holographic lenses. Journal of Optics, 13, 53–57.
[22] Shakher, C., & Rao, G. V. (1987). Use of holographic optical elements in speckle metrology: Part II. Applied Optics, 26, 654–657.
[23] Shakher, C. (1988). Analysis and evaluation of a two holo-lens system imaging. Journal of Optique (Paris), 19, 27–32.
[24] Duffy, D. E. (1974). Measurement of surface displacement normal to the line of sight. Experimental Mechanics, 14, 378–384.
[25] Jayaswal, R. K., Yadav, H. L., & Barhai, P. K. (2015). Design and analysis of modified version of double aperture speckle interferometer consisting of holographic optical element: Application to measurement of in-plane displacement component. Optik, 126(18), 1700–1704.
[26] Khan, A. A., & Yadav, H. L. (2024). Experimental assessment of a low-cost aberration-free compact double aperture four-hololens imaging system: Application to the enhancement of sensitivity and accuracy of in-plane displacement measurement. Applied Optics, 63, 3069–3078.
[27] INTEGRAF LLC. (n.d.). *PFG-01 holographic film plates*. https://www.integraf.com/shop/pfg-01-holographic-film-plates
[28] Mehta, P. C., & Rampal, V. V. (1993). Lasers and holography. World Scientific.
[29] Collier, R. J., Burckhardt, C. B., & Lin, L. H. (1971). Optical holography. Academic Press.
[30] Sirohi, R. S. (1993). Speckle metrology. Marcel Dekker.