Design and Analysis of Double-Aperture Holospeckle Interferometer Using Compact Holographic Lenses

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Abstract

In present work, a double aperture speckle interferometer using compact two holographic lenses has been fabricated and used in speckle metrology to measure in-plane displacement component parallel to the line joining the two apertures. Theoretical analysis presented reveals that diffraction limited performance almost free from all monochromatic aberrations can be achieved over the two apertures under proper recording and playback geometry. Experimental results are in good agreement with the actual displacement given to the object between two exposures. Based on experimental investigations it is established that light weight, compact and low cost holographic optics can be used advantageously to obtain diffraction limited imaging performance in speckle metrology. Such imaging system finds application in fracture mechanics.

Keywords: Hololens, Diffraction limited optics, Speckle metrology.

Introduction

Duffy [1] suggested the use of double-aperture imaging system in speckle metrology for the measurement of in-plane displacement component parallel to the line joining the two apertures. In this arrangement, twin apertures are placed symmetrically over the imaging lens. As pointed out by Duffy the imaging lens used in such configuration need not be diffraction limited over the entire lens aperture, but only over the two small areas encompassed by the two apertures. Archbold and Ennos [2] and Stetson
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[3] pointed out that in speckle photography aberrations of the imaging system puts a limit on accuracy of measurement, especially, when the displacement of the object points are complex and large. To get rid of effect of aberration, Shakher and Rao [4] investigated the use of holographic lenses in speckle metrology and achieved almost diffraction limited performance.

Subsequently, Shakher and Yadav [5] used a two hololens imaging system in speckle metrology to measure crack mouth opening displacement (CMOD) and crack tip opening displacement (CTOD) experimentally in an aluminium beam specimen having central edge crack subjected to three point bending. Use of a standard imaging system [1,2] or two hololens imaging system [4,5] in speckle metrology leads to the measurement of vector displacement at the crack mouth, which has to be resolved further into X- or Y- component to get CMOD. Therefore, measurement of fringe orientation ‘θ’ with respect to X or Y-axes becomes necessary. Use of Duffy’s double aperture imaging system in speckle metrology may be advantageous than that of standard imaging system [1,2] or two hololens imaging system [4,5] where measurement of in-plane displacement component along a particular direction is required, especially as in case of measurement of CMOD or CTOD. Further, Yadav et.al. [6] fabricated a double aperture speckle interferometer using four holographic lenses and used it in speckle metrology to measure (CMOD) in an aluminium beam specimen having central edge crack subjected to three point bending. Alignment of holographic lenses as cited in reference [6] is difficult and time consuming. In order to avoid cumbersome alignment process, in present work, a system of only two holographic lenses of large diameter were recorded on high resolution holographic plate and cemented together with proper alignment. Twin apertures were placed symmetrically over the compact holographic lens system to fabricate double aperture speckle interferometer. The present imaging system was used to measure in-plane displacement parallel to the line joining the two apertures. The experimental results are in good agreement with the actual displacement given to the diffused object.

**Lens recording and playback geometry**

Two identical hololens HL₁ and HL₂ used in the imaging system were recorded on high resolution holographic plate (PFG-01) using He-Ne laser. The angle between the two beams (45°) was optimized to achieve high efficiency operation at all points of lens aperture. The schematic of the recording geometry for recording hololens is shown in fig.1. To prevent formation of spurious grating, lenses were recorded in the index-matched conditions and films were processed using reversal bleach process [7] to enhance diffraction efficiency and to minimize scattering noise.

Fig.2 shows the schematic of a typical double-aperture compact hololens imaging system. The lenses HL₁ and HL₂ were used in the system after being rotated through 180° with respect to the axis perpendicular to plane of fig.1 to obtain a plane wavefront from each object point through HL₁ and a real point focus from a plane wavefront through HL₂. The lenses were aligned properly and cemented together to form a compact hololens system. Twin apertures were placed symmetrically along X axis (say) over the imaging lens similar to Duffy’s double aperture arrangement [1].
For the present imaging configuration, a spherical diverging wave coming out of a point object and passing through twin apertures is transformed into a plane wavefront by HL₁, which is transformed into a converging wave by HL₂ to give real image of the object point.

Figure 1: Schematic of the experimental set-up for recording holographic lenses.

Figure 2: Schematic of a typical double aperture compact hololenses imaging system.
Analysis

The radius of curvature of wave propagated through either apertures of HL$_1$ is given by

$$\frac{1}{R_i} = \frac{1}{R_c} \pm \mu \left( \frac{1}{R_{O_i}} - \frac{1}{R_{r_i}} \right)$$  \hspace{1cm} (1)

Where the subscript $I$, $C$, $O$ and $r$ stand for image, reconstruction, object and reference beam for hololens-HL$_1$.

Where $\mu = \frac{\lambda_c}{\lambda_r} = 1$ is the ratio of the wavelength of light used when reconstructing and recording the holograms. The $\pm$ signs normally denotes ‘+’ for a virtual image and ‘-’ for a real image. As the hololens HL$_1$ is used in the imaging system after being rotated through $180^\circ$ with respect to the axis perpendicular to fig.1 and played back by diverging beam so as to get real point focus so we take ‘-’ sign in equation (1) i.e.

$$\frac{1}{R_i} = \frac{1}{R_c} - \left( \frac{1}{R_{O_i}} - \frac{1}{R_{r_i}} \right)$$  \hspace{1cm} (2)

In present playback geometry object wave now behaves as reconstructing wave, hence,

$R_{c_i} = R_{O_i}$

$R_{r_i} = R_{r_i}$

But $R_{r_i} = \infty \therefore R_{r_i} = \infty$

i.e. out coming beam from HL$_1$ is plane wave. The hololens HL$_2$ is used in the imaging system after rotating through $180^\circ$ with respect to the axis perpendicular to the plane of fig.1 and is illuminated by a plane wavefront generated by HL$_1$ so as to get real point focus. The radius of curvature of the wave propagated from HL$_2$ is given by

$$\frac{1}{R_{r_2}} = \frac{1}{R_{c_2}} - \left( \frac{1}{R_{O_2}} - \frac{1}{R_{r_2}} \right)$$  \hspace{1cm} (3)

Here $R_{c_2} = R_{r_2} = \infty$

$R_{r_2} = -R_{O_2}$

This shows that the radius of curvature of the wave coming out of HL$_2$ is equal in magnitude to the radius of curvature of the object wave. The ‘-’ sign shows that out going wave is converging one because recording geometry shows that $R_{O_2}$ is diverging wave.

To assess the aberrations introduced by HL$_1$ and HL$_2$ for the conditions under which they are fabricated and used in the system we use expressions given by Meir [8] and Champagne [9]. The coefficient of spherical aberration ($S$), Coma ($C_x$, $C_y$),
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astigmatism \((A_x, A_y, A_z)\), curvature of field \((F)\) and distortion \((D_x, D_y)\) can be written as

\[
S = \frac{1}{R_c^3} \left( \frac{1}{R_o^3} - \frac{1}{R_r^3} \right) \cdot \frac{1}{R_i^3},
\]

\[
C_x = \frac{x_r}{R_c} \cdot \left( \frac{x_o}{R_o^3} - \frac{x_r}{R_r^3} \right) \cdot \frac{x_i}{R_i^3},
\]

\[
C_y = \frac{y_r}{R_c} \cdot \left( \frac{y_o}{R_o^3} - \frac{y_r}{R_r^3} \right) \cdot \frac{y_i}{R_i^3},
\]

\[
A_x = \frac{x^2_r}{R_c^3} \cdot \left( \frac{x_o^2}{R_o^3} - \frac{x_r^2}{R_r^3} \right) \cdot \frac{x_i}{R_i^3},
\]

\[
A_y = \frac{y^2_r}{R_c^3} \cdot \left( \frac{y_o^2}{R_o^3} - \frac{y_r^2}{R_r^3} \right) \cdot \frac{y_i}{R_i^3},
\]

\[
A_{xy} = \frac{x_r y_r}{R_c^3} \cdot \left( \frac{x_o y_o}{R_o^3} - \frac{x_r y_r}{R_r^3} \right) \cdot \frac{x_i y_i}{R_i^3},
\]

\[
F = \frac{x^2_c + y^2_c}{R_c^3} - \frac{x_o^2 + y_o^2}{R_o^3} + \frac{x^2_r + y^2_r}{R_r^3} - \frac{x_i^2 + y_i^2}{R_i^3},
\]

\[
D_x = \frac{x^3_c + x_r y^2_c}{R_c^3} - \frac{x^3_o + x_o y^2_o}{R_o^3} + \frac{x^3_r + x_r y^2_r}{R_r^3} - \frac{x_i^3 + x_i y^2_i}{R_i^3},
\]

\[
D_y = \frac{y^3_c + y_r x^2_c}{R_c^3} - \frac{y^3_o + y_o x^2_o}{R_o^3} + \frac{y^3_r + y_r x^2_r}{R_r^3} - \frac{y_i^3 + y_i x^2_i}{R_i^3},
\]

Where \((x_c, y_c), (x_o, y_o), (x_r, y_r)\) \((x_i, y_i)\) are coordinates of the constructing, object, reference and reconstruction beams.

We see that a plane wave propagate between two hololenses i.e. \(R_o = \infty\) and played back after rotating it through \(180^\circ\). Under condition \(x_{ci} = x_{ci}, y_{ci} = y_{ci}, R_{ci} = -R_{ci}\), the coefficient of spherical aberrations \((S)\), coma \((C_x, C_y)\), astigmatism \((A_x, A_y, A_z)\), field of curvature \((F)\) and distortion \((D_x, D_y)\) become zero.

The reconstructed beam from the first lens HL1 acts as reconstructing beam for the second lens HL2, under the condition,

\[
R_{ci} = R_{ci} = \infty, R_{ci} = -R_{ci}, x_{ci} = x_{ci}, y_{ci} = y_{ci}.
\]

The coefficient of spherical aberration(s), coma \((C_x, C_y)\), astigmatism \((A_x, A_y, A_z)\), field curvature \((F)\) and distortion \((D_x, D_y)\) for HL2 also becomes zero.
Experimental

A diffused object illuminated with an expanded laser beam ($\lambda = 0.6328 \mu m$) was imaged with the help of double-aperture hololens imaging system as shown in figure 3. Double-exposure specklegrams were recorded on the same high resolution plate; one with object in its initial position and the other where object has undergone in plane translation parallel to line joining the two apertures. To monitor the displacement given to the diffused object between two exposures motion controller/driver (XPS Newport) was used.

Table 1 gives the Comparison of actual displacement given to the object parallel to the joining the two apertures and measured values of in-plane displacement component (displacement along X-axis) using double exposure photography where a double aperture imaging system was used. The values of in-plane displacement component were calculated by analyzing the double-exposure speckle grams using a point-by-point filtering technique [2].

<table>
<thead>
<tr>
<th>Displacement given to object as recorded by Microcontroller</th>
<th>Displacement measured by analyzing specklegram</th>
<th>% Error</th>
</tr>
</thead>
<tbody>
<tr>
<td>10 µm</td>
<td>10.5 µm</td>
<td>5</td>
</tr>
<tr>
<td>15 µm</td>
<td>15.9 µm</td>
<td>6</td>
</tr>
<tr>
<td>20 µm</td>
<td>21.0 µm</td>
<td>5</td>
</tr>
<tr>
<td>25 µm</td>
<td>26.5 µm</td>
<td>5</td>
</tr>
<tr>
<td>30 µm</td>
<td>31.8 µm</td>
<td>6</td>
</tr>
</tbody>
</table>

Figure 3: Schematic of experimental set-up for measurement of in plane displacement component.
**Discussion/Conclusion**

Present investigation shows that experimental results are in good agreement with the actual displacement given to the object between two exposures and as measured by a motion controller. Hence, low cost double-aperture compact hololens imaging system can be used advantageously in speckle metrology to obtain diffraction limited performance. Such systems are useful measuring in-plane displacement component.

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**References**


