MULTI WAVELENGTH METHODS IN HOLOGRAPHIC INTERFEROMETRY

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Abstract

Techniques are presented which take advantage of the wavelength dependence of various phenomena in holographic interferometry. Image-plane interferograms illuminated with light containing multiple wavelengths exhibit color dispersion of the fringes. We extract from this dispersion, full- field information concerning displacement components which are not disclosed by monochromatic illumination.

Theoretical background: wavelength dependent effects during reconstruction

Consider a holographic interferogram formed with light of wavelength λ. If the interferogram is illuminated with light of the same wavelength, the fringe order n of a given object point is given by[1]

$$D = n\lambda = \mathbf{u}\cdot(\mathbf{k} - \mathbf{h}). \qquad (1)$$

in which D is the optical path difference, **u** is the displacement vector of the object point, **k** is the observation unit vector from the object to the eye and **h** is the object illumination unit vector from the source to the object. If, however, the interferogram is reconstructed by light of a different wavelength λ', the optical path difference [2] is given by

$$D' = [\lambda'/\lambda]\mathbf{u}\cdot(\mathbf{k} - \mathbf{h}). \qquad (2)$$

When a fringe of given order is viewed by light of wavelength λ', the observation direction becomes **k'**, not **k**. The relation between these vectors has been given recently [2], for a hologram which experiences no deformation,

$$\mathbf{N}\{[1/\lambda'](\mathbf{k}' - \mathbf{c}') - [1/\lambda](\mathbf{k} - \mathbf{c})\} = 0, \qquad (3)$$

in which **N** is a projection operator, **c** is the unit vector from the reference source to the hologram, and **c'** is the unit vector from the reconstruction source to the hologram. The operator **N** acts upon a vector **v**, to give the normal projection of that vector on the hologram plane: **Nv = v - n[v·n]**, in which **n** is a unit vector normal to the hologram. Applications [2] of such theoretical developments have centered principally upon the problem of reconstruction using a gas laser, eg. helium neon at 633 nm, of holograms made with high power pulsed lasers, eg. ruby at 694 nm, a different wavelength.

Wavelength dependence of fringe order in image-plane holograms

In this article we consider applications in which multiple wavelengths are deliberately introduced at the reconstruction to display additional information about the object displacement field. The hologram itself is not deformed. To that end, let Eq. 3 be satisfied by setting the vector in the {} brackets equal to zero. We obtain the following from Eqs. 2 and 3.

$$n'\lambda' = D' = \mathbf{u}\cdot(\mathbf{k}' - \mathbf{h}) + \mathbf{u}\cdot(\mathbf{c} - \mathbf{h})[(\lambda'/\lambda) - 1] + \mathbf{u}\cdot(\mathbf{c} - \mathbf{c}') \qquad (4)$$

or equivalently,

$$n' = [1/\lambda][\mathbf{u}\cdot(\mathbf{k}' - \mathbf{h}) + \mathbf{u}\cdot\mathbf{k}'[(\lambda/\lambda') - 1] + \mathbf{u}\cdot(\mathbf{c} - (\lambda/\lambda')\mathbf{c}')] \qquad (5)$$

in which n' is the new fringe order at the reconstruction and λ' is the wavelength of reconstruction light. If the reconstruction light direction **c'** is identical to the reference light direction **c**, Eqs 4 and 5 become simplified.

The distance between object points and the hologram plane does not appear in Eqs. 4 or 5. They may be therefore applied either to an off-axis hologram or to an image-plane hologram. Image-plane holographic interferometry by the lens method has several advantages over off-axis holography: speckle can be reduced by illumination in non-laser light, the images can be viewed convieniently in white light, and the image quality and resolvable fringe density are superior to off-axis holography [4,5]. Off-axis hologram images are severely blurred when viewed in white light, although the fringes may be clear.

Multi wavelength illumination is therefore best suited for image-plane holograms. If a lens system is used to produce the image-plane hologram, we shall assume at this juncture a unity magnification configuration to prevent distortion of the object or its displacement field. In an image-plane hologram, points on the object which are imaged into the hologram plane will be sharply imaged and will not move under a change of wavelength even though the fringe order may change. When such a hologram is illuminated by a source containing multiple wavelengths, the object surface focused on the hologram plane appears without blur. The fringes, however, may be localized off the object surface and may be multicolored due to wavelength dispersion. The dispersion of the fringes for each object point is determined from Eq. 4 or Eq. 5 by

$$dn'/d\lambda' = [1/\lambda'^2]\mathbf{u}\cdot[\mathbf{c}' - \mathbf{k}']. \qquad (6)$$

Observe that an object point for which $\mathbf{u}\cdot(\mathbf{c}' - \mathbf{k}') = 0$ will exhibit zero color dispersion and will therefore be achromatic, provided a sufficient range of wavelengths is diffracted into the eye. Observe that the achromatic points are stationary with respect to the object, ie. independent of view direction **k'**, if (i) the vectorial displacement of the object point is zero, or (ii) if the observer moves his eye in a direction for which there is no displacement component so that $\mathbf{u}\cdot\Delta\mathbf{k}' = 0$. Otherwise the achromatic point will move with respect to the object as the viewing eye is moved.

Identification of zero displacement points

Wavelength dependent phenomena offer several possibilities to enhance the conventional zero-order fringe method [1-3]. In this method, the component of displacement along a particular direction is determined from the fringe order via Eq. 1. If an absolute measurement of displacement is desired, the zero-order fringe [corresponding to $\mathbf{u}\cdot(\mathbf{k}' - \mathbf{h}) = 0$] must be identified, a process which usually requires forethought in the preparation of the holographic interferogram and which can be problematical [3]. If wavelength dependent effects are utilized, one may determine in a *post hoc* manner, which points in an interferogram have experienced zero displacement. Let the hologram be viewed in white light. Eqs. 4 or 5 imply that an achromatic point signifies a zero component of displacement in a direction along (**c' - k'**). If the displacement is in fact zero at a point, there will also be zero parallax of the fringe with respect to the object point [1,3]. Moreover, fringes upon such an object point will remain achromatic independent of view angle.

Simultaneous display of displacement components in several directions

In the simplest form of the zero order fringe method, the component of displacement along the line of sight is obtained by preparing the object illumination to be along the line of sight [3] and using Eq. 1 [which then simplifies to $u_z = n\lambda/2$ if the z axis is along the line of sight] for interpretation. Ordinarily, the other components are obtained by applying the relative fringe method, also known as the dynamic or fringe counting method or by applying the zero-order fringe method to a different hologram of the same object [1,3]. Now, if the experimenter uses light of a different wavelength or light containing multiple wavelengths at reconstruction, components along (**c' - k'**) may be extracted by virtue of the fact that the second and third terms in Eq. 5 offer a new sensitivity direction. If the displacement is not too large, illumination of the hologram by white light discloses fringes with color dispersion related to displacement in a direction along (**c' - k'**), according to Eq. 6. Such an image encodes additional information about the motion in a full-field manner. Quantitative data may be obtained by evaluating the fringe order for light of multiple, known discrete wavelengths. The direction and magnitude of the sensitivity vector (**c' - k'**) for the color effect can be controlled by proper choice of **c'** and **k'**. It can be made nearly orthogonal to the line of sight by choosing appropriate reference beam and observation directions. For large displacement along this sensitivity direction, color blur may be excessive when the object is viewed with a multi wavelength source. In that case, the displacement can be evaluated by illuminating the hologram with light of adjustable wavelength, e.g. from a monochromator. The component of displacement along (**c' - k'**) is evaluated from the rate of change of fringe order with wavelength according to Eq. 6. Since this is a differential measurement, a component of absolute displacement can be obtained even if no zero-order fringe is present in the hologram.

Removal of ambiguities in sign

Observe that in Eq. 5 the first term is identical to that in conventional holographic interferometry; a fringe pattern of this type does not reveal which fringe is the zero order fringe nor does it reveal the sign of the displacements. The second and third terms incorporate color fringing effects due to motion in a different direction. The sense of this motion component is encoded in the direction of color dispersion of the fringe, as given in Eq. 6. The direction of the displacement vector remains ambiguous since no evidence appears in the fringe pattern, of the order in which the holographic exposures were taken.

Lens holography: unequal conjugates

In previous studies involving lens holographic interferometry [4,5], the zero order fringe method was used for interpretation. The view direction was along the optic axis, consequently no modification of the interpretation relations was needed. When the dynamic fringe counting method is used, the presence of a lens in the system can make a substantial difference. In the dynamic method, the observer views an object point from one view angle $\mathbf{k_1}$, sweeps to a second view angle $\mathbf{k_2}$ and counts the number of fringes Δn which pass some fixed point of interest on the object [1,3]. The relation for interpretation is, for monochromatic light [1]:

$$\Delta n\lambda = u\cdot(k_1 - k_2)$$

For a change of wavelength at reconstruction we have, from Eq. 4:

$$\Delta n'\lambda' = u\cdot(k'_1 - k'_2)$$

Now if a lens is used, the apparent view direction differs from the direction of light reflected from the object, as shown in Fig. 1. As for the view angle α which enters the difference in observation unit vectors $(k_1 - k_2)$, the view angle β for the image will differ from the view angle α for the object unless the lens sytem is set up for unity magnification. If the magnification is less than one, $\beta > \alpha$ and the sensitivity of the dynamic method to in-plane motion is reduced; if the magnification is greater than one, the sensitivity is increased. Such magnification effects have also been interpreted in terms of correlation radii and depth of focus of the fringe localization point [4]. As for the use of multiple wavelengths for reconstruction, we remark that the sensitivity direction for color dispersion will normally be nearly orthogonal to the line of sight as in the dynamic fringe counting method. Consequently color dispersion is expected to be reduced in the lens method if the magnification is less than one. Moreover, the apparent depth of the object will be reduced in such a demagnified image, since the longitudinal magnification is the square of the transverse magnification.

Experimental Results

Holographic interferograms were made using the configuration shown in Fig. 1. Exposures were made on Agfa 8E75 plates using light from a 15 mW helium neon laser at 633 nm. The reference beam was collimated, in a horizontal plane, and 36° from the normal to the plate. The object was a prismatic beam, 18 mm by 22 mm in cross section, of rigid polyurethane foam, supported by bolts at one end and by a roller at an intermediate point, upon a massive steel base. A dead weight load of 100 g was applied at the free end. Several types of lens were used to image the object upon the holographic plate.

Fringes were observed in laser light at 633nm, in combined light of helium neon and helium cadmium lasers at 633 nm and 442 nm respectively, and in white light from a halogen projector lamp. The reconstruction beam geometry was first set identical to the reference beam geometry. In two wavelength illumination the grid marks upon the object coincided (within a small focus error), but the fringes did not. Moreover, reconstructed circular vignetting pupil images of the lens were observed behind the holographic plate; the red pupil coincided with the original position of the lens and the blue pupil was smaller and displaced to one side. In holograms made with an f/1.2 lens, the red and blue pupils were sufficiently large that they intersected, so that it was possible to see, from a single viewing location, a portion of the object reconstructed in both red and blue light. When conjugate illumination was used, the lens pupils were imaged in front of the plate, in the viewer's space, so that the entire object was visible in both red and blue. In white light illumination, the circular pupil images were not seen, owing to the continuous distribution of wavelengths. Instead, the image was observed to be polychromatic, with red dominating on one side and blue on the other. Conjugate illumination reduced this polychromaticity, although the fringes themselves still exhibited color dispersion.

Interferograms made with a 121 mm diameter, six element, f/1.2 lens system and illuminated with a conjugate beam of white light are shown in figures 2 and 3. A magnification of unity was chosen so that the relation between longitudinal and lateral motions was preserved. In making the hologram which is reconstructed in Fig. 2, object illumination was in a horizontal plane, 24° from the optic axis. In observation of the reconstructed image, the neutral axis of bending is identified by the absence of color dispersion along the bar's midline.The color dispersion changes direction across the midline. In making the hologram shown in Fig. 3, the bending configuration was the same, but the object illumination was angulated in the vertical direction, resulting in a different fringe pattern. Nevertheless the neutral axis is identifiable as a zone of zero color dispersion and as a transition locus where the direction of color dispersion changes. In these images there is residual polychromaticity across the object, despite the use of conjugate illumination. The hologram was photographed using a macro lens of 100 mm focal length, which had to be placed relatively close to the plate. The macro lens consequently accepted light over a range of angles, resulting in the polychromaticity. This was not noticed when the hologram was viewed from further away.

Demagnified lens interferograms of the bent bar were made using a cemented doublet lens of 40 mm diameter and 150 mm focal length. These interferograms were observed in laser light to exhibit fringe patterns similar to off-axis interferograms and to lens interferograms of unity magnification. In white light illumination, however, the demagnified fringes exhibited less color dispersion than the ones with unity magnification, as predicted. Interferograms were also made at various magnifications with a $f/1.4$ camera lens of focal length 50 mm. Fringe patterns and color effects were the same as reported above, except that the image space was restricted by the lens size.

Discussion

Color blur of fringes in white light illumination is not simply a result of a parallax effect, by contrast to the color blur of *object* points which lie off the hologram plane. Fringes localized on the object surface will exhibit color blur if they were formed as a result of a displacement with a component in the direction of ($\mathbf{c}' - \mathbf{k}'$). The color effects encode information concerning displacement in several directions in a full field manner. The vectorial displacement of each point on the object can also be extracted from the hologram using both the zero order fringe and fringe counting methods, however only one displacement direction is then displayed in a full field way; the others are extracted pointwise.

There is a relation between the type of lens used and the range of wavelengths which are diffracted into the viewing eye from a particular image point. A large aperture (small f number) lens is desired, so that both the view angle and the range of wavelength diffracted into the viewing eye is maximized. A similar limitation occurs in the case of off-axis holograms: the maximum angle which the eye may traverse while viewing an object point is limited by the size of the hologram in relation to the object distance.

We remark that the original derivation of Eq. 3 was based on consideration of holographic aberration following a modification at the reconstruction [2]. In lens image-plane holography, there is the possibility of aberration due to the lens. There is consequently a lower bound upon the quality of the lens used to produce image-plane holograms which are to be interpreted using the wavelength- dependent effects discusssed here. Such limitations were not apparent in the lenses used in this study.

Other approaches involving color in holographic interferometry have been proposed. Specifically, multiple slit apertures have been used in one-step Benton lens holography to achieve white-light viewing of an interference pattern from two directions [6]. Multiple laser wavelengths have been used in the formation of one-step Benton lens holograms to color code different physical effects [7]. The present approach, by contrast, uses no slit pupil. Consequently no information is sacrificed in the recording step, so that conventional interpretation schemes can still be used for these holograms. However, deep images will not reconstruct clearly in white light.

We view the present approach to be most useful as a tool for the rapid screening and evaluation of image-plane interferograms. No new information is provided: the displacement information revealed by a multi wavelength approach may also be extracted by standard interpretation methods. A multi wavelength approach, however, provides a full field picture in contrast to the tedious pointwise measurements used in the fringe counting method for in plane motion.

References

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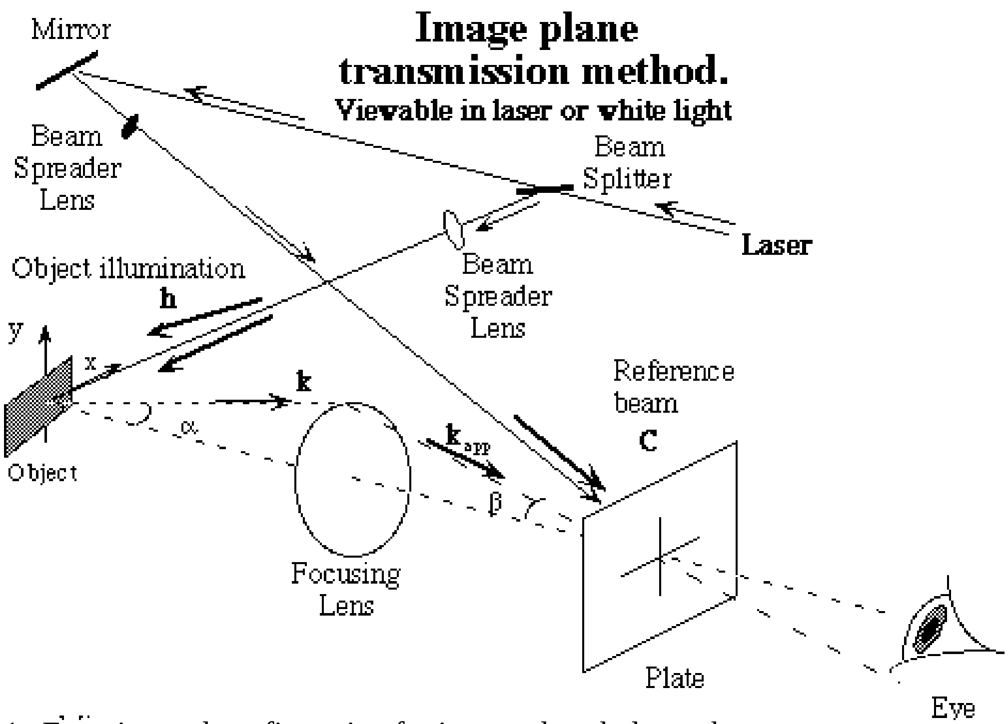
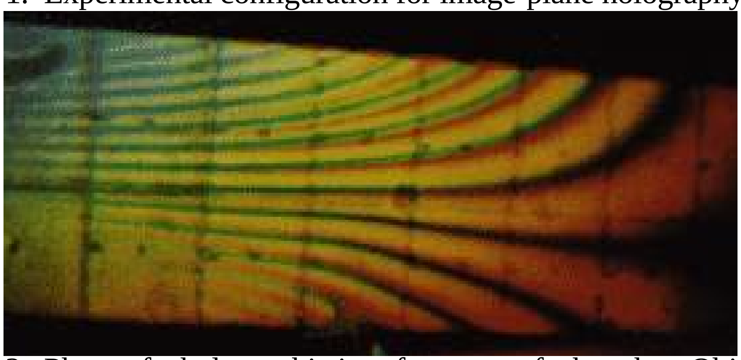
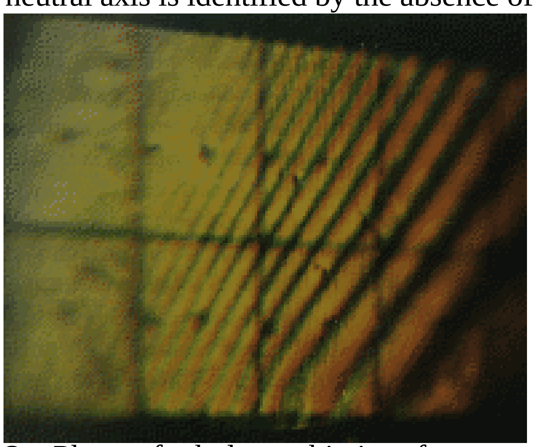


1. Experimental configuration for image-plane holography.



2. Photo of a holographic interferogram of a bent bar. Object illumination was by laser light at 633 nm, in a horizontal plane, 24° from the optic axis. Reconstruction was by conjugate white light. The neutral axis is identified by the absence of color dispersion.



3. Photo of a holographic interferogram of a bent bar with the same load condition as in Fig. 2. Object illumination was by oblique laser light at 633 nm, 56° from the horizontal. Reconstruction was by conjugate white light. The neutral axis is again identified by the absence of color dispersion.