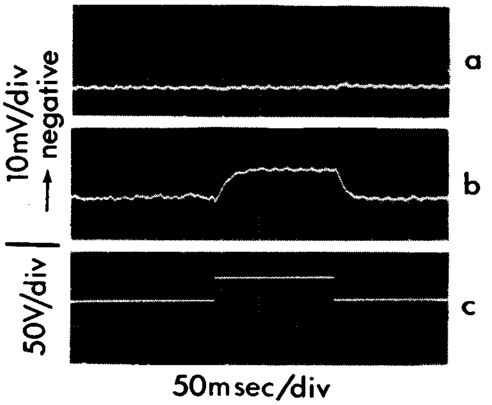


FIG. 2. (a) Trace obtained during activation of the piezoelectric driver when no impalement is made by the electrode. (b) Impalement of a bull sperm head showing a potential of −9 mV. The slow response time of the amplifier (20 msec) is due to the capacity of the cable which connects the electrode. (c) Driving pulse used to activate piezoelectric crystals.

The device has been used successfully to impale the heads of single bull spermatozoa[2]. In Fig. 2, a tracing obtained from such impalement shows a potential of −9 mV in the bull sperm head.

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[1] J. Tupper and R. Rikmenspoel, Rev. Sci. Instrum. **40**, 851 (1968).

[2] C. Lindemann and R. Rikmenspoel, J. Cell Biol., Abstr. **47**, 124a (1970).

## Continuous Phase Control in Holography

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SEVERAL different techniques have been used to alter the phase between reference and object beams in holographic applications. These methods are employed to regulate holographic fringe stability, vary fringe density, and provide intentional phase shifts in holography and holographic interferometry. In general, the phase can be modified by introducing relative path length changes or refractive index variations in either beam. Path length changes without beam rotation are achieved by mechanical translation of a mirror in a direction parallel to the beam axis, as in a Michelson interferometer, or rotation of an optical flat in a collimated beam about an axis normal to the beam.[1] In the latter case, beam displacements normal to the axis are usually small and can be neglected. Fringe spacing or density is unaltered with these techniques. The use of rotating mirrors, plates, and prisms for phase control[2,3] couples path length variations with beam rotation and consequently yields variable interference fringe densities.

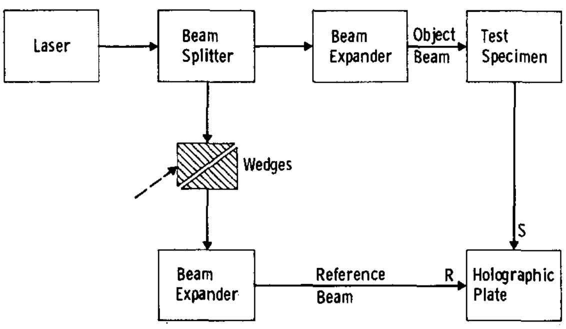


FIG. 1. An optical system for phase controlled holography.

The use of refractive index changes to control phase is illustrated by the air cell design of Wilson and Strope.[4] Refractive index variations are obtained by changing the air pressure or temperature in the cell. In a demonstration of image synthesis by holographic addition, Stroke[5] introduced a discrete ($\pi$ rad) phase shift in a double exposure holographic subtraction experiment by means of a half-wave retardation plate.

A new method has been devised to control the relative phase between reference and object beams in a continuous manner. Advantages of this technique are stated below. Two identical wedges are placed in either parallel beam of a holographic system as shown in Fig. 1. Inclined wedge surfaces are facing each other but are not in contact. One wedge is held fixed in position; the other can be translated as indicated in the figure. Collectively the wedges form a plate with parallel entrance and exit surfaces. The equivalent plate thickness is altered by translation of the movable wedge. Rate of change of equivalent thickness with translation motion is determined by the wedge angle. If $\Delta d$ represents a change in equivalent thickness, the resulting phase change is $\Delta\phi = 2\pi n\, \Delta d/\lambda$, where $\lambda$ is the laser wavelength and $n$ the refractive index of the wedge material. The exit beam is transversely displaced due to the air gap between wedges. If the wedges are moved in a direction parallel to the sloping faces the air gap separation remains constant. Hence the exit beam displacement would also be constant.

Such wedge configurations are contained in commercially available Soleil and Babinet compensators, commonly used in polarization studies. The movable wedge is operated with a micrometer drive and can easily be calibrated to read path or phase difference directly. The Soleil compensator contains two wedges with the same refractive index and a plane parallel plate of a different refractive index, which is nonfunctional in this application. The two wedges together form a plane parallel plate whose equivalent thickness can be changed by translating one of the wedges. For this compensator the phase shift is uniform over the full aperture of the wedge assembly and would be appropriate for use with large laser beam diameters. However, it is advantageous to insert the Soleil compensator into the narrow laser beam, before

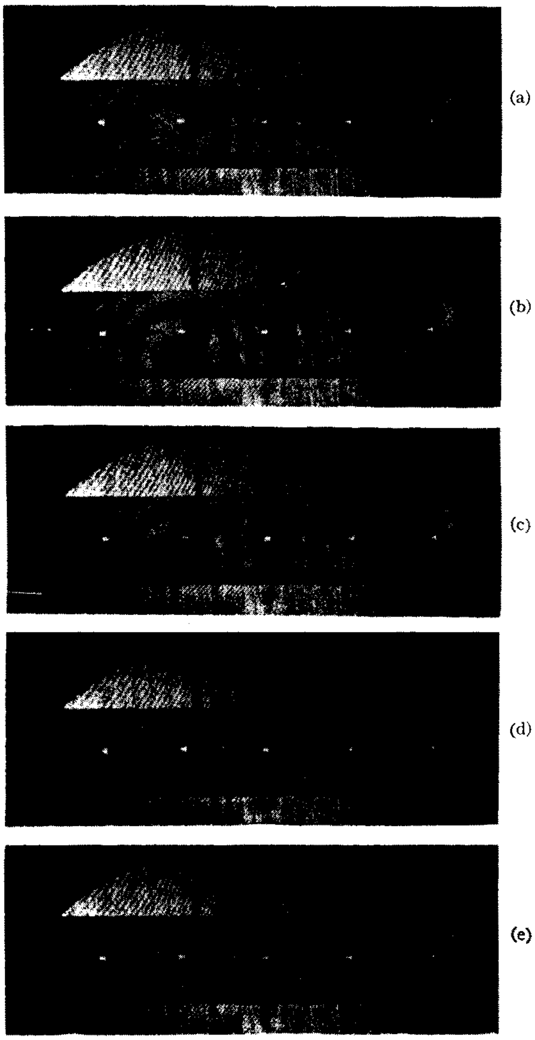


FIG. 2. Fringe pattern changes due to controlled phase differences in holographic interferometry.

the spatial filter and beam expansion components, since typical compensator apertures are small (of the order of 1 cm) and could limit the exit beam diameter. Furthermore, the spatial filter serves to remove beam distortions and noise introduced by possible optical flaws in the unit. In the Babinet compensator the wedges have different refractive indices (owing to the perpendicular orientation of the optic axis of wedge materials). As a result, the optical path difference varies continuously along the length of the wedges. Hence the desired phase shift is achieved only over a narrow portion of the wedge assembly. This may not be objectionable with very narrow laser beams. In commercially available compensators of both types the movable wedge is translated parallel to the entrance or exit face. Thus the air gap thickness and consequently the exit beam displacement changes. This displacement can be made sufficiently small by using small wedge angles.

Figure 2 illustrates how continuous phase control with a wedge configuration can complement holographic interferometric experiments. A single exposure hologram was made of a test specimen (an end supported flat metallic strip with several machined holes). The holographic plate was developed and carefully repositioned into the optical system by using a specially designed six-degree-of-freedom plate holder. With the specimen slightly deformed, a system of coarse, circular fringes is observed when one is simultaneously viewing the illuminated object and the holographic virtual image [Fig. 2(a)]. If $x$ represents an effective path difference between rays emanating from an identical point on both the specimen and the virtual image, then a dark fringe describes the locus of points for which $2\pi x/\lambda+\phi=(2m+1)\pi$, where $m$ is an integer indicative of the fringe order and $\phi$ is an arbitrary phase term. By driving the movable wedge in the wedge assembly, the value of this phase term can be changed at will. The sequence illustrated in Fig. 2 demonstrates how the fringe pattern is altered as $\phi$ is increased. For this case the circular fringes appear to emerge from the center when they are visually observed as the relative phase is changed. (A linear fringe pattern would appear to be swept across the field of view.) The resulting fringe pattern for a phase shift of about 180° is shown in Fig. 2(c). Note that the center of the fringe pattern is now predominantly dark. As the phase change is further increased to about 360°

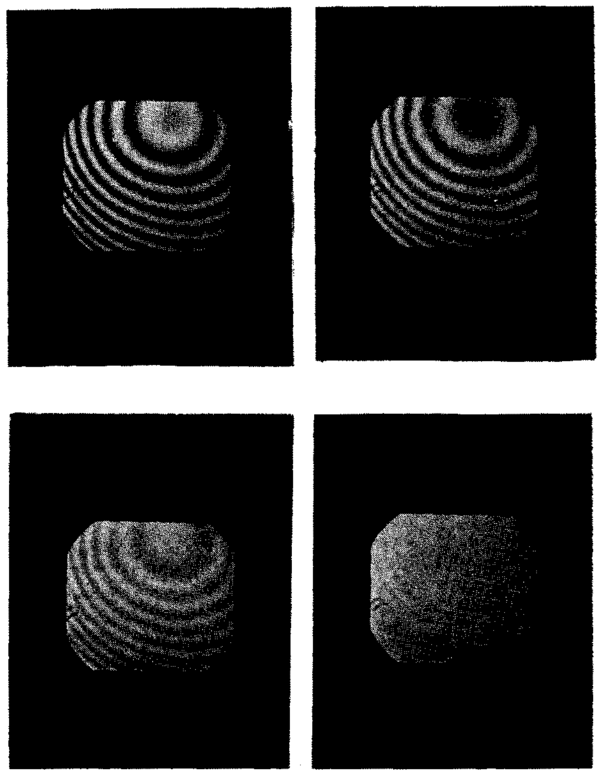

FIG. 3. Continuous complex addition with phase control. Upper left, $\phi=0°$; upper right, $\phi=45°$; lower left, $\phi=90°$; lower right, $\phi=180°$.

the fringe pattern is restored to its original geometry, as in Fig. 2(e). This corresponds to a change in fringe order of unity; i.e., $m$ goes to $m\pm 1$. Thus changes can be measured in effective path $\Delta x$ at any point in the field of view of the superposed illuminated object and holographic image. This is achieved by bringing a neighboring dark fringe to the desired location when changing the relative phase of either the illumination or reconstruction beam. If the phase shift $\Delta\phi$ is known, then the change in path $\Delta x$ can be readily determined from $|2\pi\Delta x/\lambda|=|\Delta\phi|$, where $|\Delta\phi|\leq\pi$.

A second example illustrates the ease with which continuous complex addition or subtraction can be achieved by a holographic double exposure technique using this phase control method. For the $j$th exposure, let $R_j$ represent the reference beam amplitude at any point on the film. The recorded transmittance pattern of holographic interest is proportional to $\Sigma_j R^*_jS_j+R_jS^*_j$, neglecting film nonlinearities. Let the reference beam phase be changed from $R_1$ to $R_2=R_1\exp(-j\phi)$ between exposures. After the second exposure the net transmittance pattern $T$ is proportional to

$$T\sim(R^*_1S_1+R_1S^*_1)+(R^*_2S_2+R_2S^*_2)$$
$$=R^*_1[S_1+S_2\exp(j\phi)]+R_1[S^*_1+S^*_2\exp(-j\phi)]. \quad (1)$$

Equal exposure times are assumed. Thus the sum of a signal $S_1$ and a phase shifted signal $S_2\exp(j\phi)$ is holographically recorded. (Note that $S_1$ and $S_2$ are in general complex quantities.) If a $\pi$ rad phase shift is introduced between exposures then $T\sim R^*_1(S_1-S_2)+R_1(S^*_1-S^*_2)$. That is, the complex signals $S_1$, $S_2$ are subtracted.

As a demonstration Fig. 3(a) shows an interference pattern from two diverging spherical wavefronts for a given setting of the wedge assembly (without double exposure). For the remaining figures in the sequence the film is first exposed with the movable wedge in its original position. Then, prior to the second half of the exposure, the relative phase $\phi$ is changed a desired amount by translating the wedge. A second exposure yields a superposed holographic recording of the two interference fringe patterns, described by Eq. (1). The sequence illustrated in Fig. 3 corresponds to relative phase changes as indicated. As the relative phase difference is increased, the fringe contrast decreases. In particular, for $\phi=\pi$, the fringe pattern is almost completely extinguished in this example since $|S_1|\approx|S_2|$.

There are several advantages in using a wedge configuration for continuous phase control in holographic experiments. First, it is well suited for use with small beam diameters or apertures, and can be included in the optical system in-line and ahead of a spatial filter. Hence the need for large, costly, high quality components such as mirrors, prisms, and optical flats for phase control can be avoided. We have found that a manually driven compensator has ample sensitivity and is convenient for static experiments, as demonstrated in the above figures. Also, such a phase control device could be readily incorporated into a feedback control system to provide automatic fringe stability within the response characteristics of the feedback loop.

Even though a commercially available Soleil compensator can introduce exit beam displacements due to its mechanical drive orientation, we have found this device to be adequate for most purposes. For situations where beam displacements cannot be tolerated, straightforward drive modifications appear feasible.

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[1] A. R. Shulman, *Optical Data Processing* (Wiley, New York, 1970), pp. 525–526.
[2] D. B. Neumann, C. F. Jacobson, and G. M. Brown, Appl. Opt. **9**, 1357 (1970).
[3] G. E. Maddux and J. G. Becsey, Rev. Sci. Instrum. **41**, 880 (1970).
[4] A. D. Wilson and D. H. Strope, Rev. Sci. Instrum. **41**, 881 (1970).
[5] G. Stroke, *An Introduction to Coherent Optics and Holography* (Academic, New York, 1966), pp. 90–96.

## Simple High Precision Position Indicator

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The electrodes of a small neon glow lamp (e.g., type NE-2) glow on alternate half-cycles when the lamp is driven by ac power. This effect and the technique of phase sensitive detection provide the basis of a simple device for accurately locating a preset (zero) position of a mechanical pointer.

The lamp is positioned close to the pointer (Fig. 1) with its electrodes parallel to the pointer. A small displacement of the pointer partially obscures one of the electrodes. A small area silicon detector opposite the lamp detects

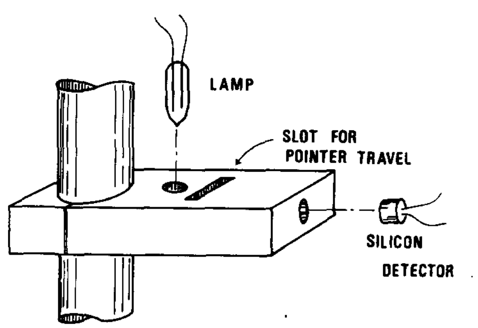


Fig. 1. Construction of position indicator.