Light-in-flight recording. 6: Experiment with view-time expansion using a skew reference wave

Pettersson, Sven-Göran; Bergstrom, Hakan; Abramson, Nils

Published in:
Applied Optics

DOI:
10.1364/AO.28.000766

1989

Light-in-flight recording. 6: Experiment with view-time expansion using a skew reference wave

Sven-Goran Pettersson, Hakan Bergstrom, and Nils Abramson

In normal light-in-flight holography the largest time difference that can be created in the image is when the reference light falls nearly parallel with the photographic plate. In that case, where the pulse front is perpendicular to the direction of propagation, the time scale on the plate is given by the speed of light. Thus the time it takes for the reference light to go from one side of the plate to the other sets the upper limit of the observable time interval. By using a reference light where the pulse front is leaning backward, this view time can be increased several times.

I. Introduction

When one uses a camera with a curtain shutter that moves to the right, the leftmost part of the photographic plate is exposed earlier than the rightmost part. Thus a time scale that depends on the velocity of the shutter can be assigned to the film. A photograph taken of a fast moving object with such a camera will distort the image of the object so that it will be shortened or lengthened in the direction of movement.

In several papers Abramson has shown[1,2] that, in light-in-flight recording, the reference pulse that travels along the photographic plate works like an ultra-high-speed curtain shutter. The reason for this is that a holographic image is only formed when the object beam and the reference beam illuminate the plate at the same time. The time scale on the plate is determined by the speed of light and the largest time difference within the image is obtained when the reference pulse travels nearly parallel to the plate. With this method it is possible to visualize the dynamics of optical phenomena but it is also possible to demonstrate some relativistic effects such as apparent rotation and distortion of objects traveling at a speed close to that of light. However, the time of viewing these phenomena is restricted to the time it takes for the reference pulse to intersect the photographic plate.

Nils Abramson is with Royal Institute of Technology, Industrial Metrology, S-100 44 Stockholm, Sweden; the other authors are with Lund Institute of Technology, Physics Department, S-221 00 Lund, Sweden.

Received 15 March 1988.
0003-6935/89/040766-05$02.00/0.

In this paper we demonstrate the possibility to increase viewing time several times by using a reference pulse that is leaning backward. This means that the time it takes for the pulse to intersect the photographic plate can be considerably increased. In a companion paper the theoretical aspects of this paper are more thoroughly developed.[3]

II. Basic Idea

As pointed out by Abramson, light-in-flight holography represents a method of gated viewing. The gating effect comes from the fact that the hologram is only sensitive to information when it is illuminated by the reference beam. For a pulsed light source this means that light must reach the plate from the object during a certain time interval to form interference fringes and thus an image. With a cw light source with limited coherence length only those parts of the object will be seen in the image that are spatially separated so that the path difference between object light and reference light is within the coherence length. In light-in-flight holography, where the image is formed due to an interference effect, a short coherence length is analogous to a short pulse of light. This is true although the light source need not be pulsed at all. Thus for a pulsed light source we get a time gating and for a cw light source we get a spatial gating. If the reference source is a small spot this gating is only dependent on the pulse length or the coherence length.

When a light-in-flight hologram is viewed with the eye scanning along the processed photographic plate a continuous motion picture of the object situation is produced. As demonstrated by Abramson this can also be used to make a motion picture of the light itself, e.g., when passing through a lens, being reflected by a mirror or being broadened by a fiber. In this case the

real object is a white screen that scatters the light toward the holographic plate.

Let us introduce a new concept for holographic recording, the light shutter. This light shutter is actually the intersecting zone of the reference pulse that moves over the photographic plate. In principle this light shutter could move with any arbitrarily chosen velocity that is not limited to the speed of light, since it is not a physical object. Let us take a closer look at what velocity we get in a normal case (Fig. 1). Since the pulse front travels with the speed of light the light shutter normally moves faster. The velocity is given by

$$v = \frac{c}{\sin\theta_i}. \tag{1}$$

Since $\sin\theta_i$ is never larger than unity, the slowest velocity is the speed of light. That means that the time it takes for the light shutter to move over the plate is very short. As an example, for a 20- × 25-cm photographic plate with the longest side horizontal, the light shutter moves over the plate in <0.83 ns. This is a rather short time interval which sets the limit on how much is seen of the propagation of the object light. However, it is often favorable to use a longer view time that makes it possible to study phenomena of longer duration.

There are some methods to increase the view time. One way is to increase the length of the plate or use a long film. The reference pulse could also move in a zigzag path reflected by mirrors at each side of the plate. The velocity of light could also be slowed down by using a material of higher refractive index in the optical setup. However, now at least one more possibility exists to increase this recording time. In our new method the pulse front of the reference light leans backward. This skew light pulse can be produced by reflecting an ordinary light pulse by a grating. In this way the time it takes for the light shutter to move over the photographic plate can be increased several times.

A light pulse can be decomposed into its Fourier components which are plane lightwaves with slightly different temporal frequencies. All these lightwaves have the same direction before the grating but after diffraction in the grating they have slightly different propagation directions. Although the wavefronts are perpendicular to the direction of propagation for each individual lightwave, the resultant pulse front is no longer perpendicular to the mean propagation direction. In Fig. 2 a light pulse was simulated by twenty different lightwaves with slightly different frequencies so that a resultant pulse was generated with a pulse length of 3 mm. The result of the simulation for this length of the pulse was identical with a trigonometric calculation based on optical path lengths. If the pulse length was considerably shorter this would not be true because of the increased dispersion. After diffraction in the grating, several light pulses with different propagation directions are formed. Only the zeroth order and the undeviated transmitted wave have a pulse front which is perpendicular to the propagation direction. For the other orders, with an angle of incidence for incoming light of γ, the angle β between the normal

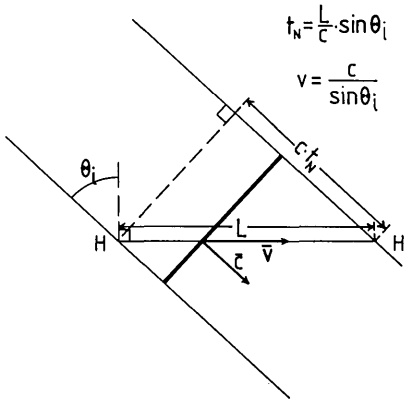


Fig. 1. Reference pulse intersects the photographic plate. The intersection works like a light shutter moving over the plate (H–H) with a velocity $\bar{v}$ faster than the speed of light $\bar{c}$.

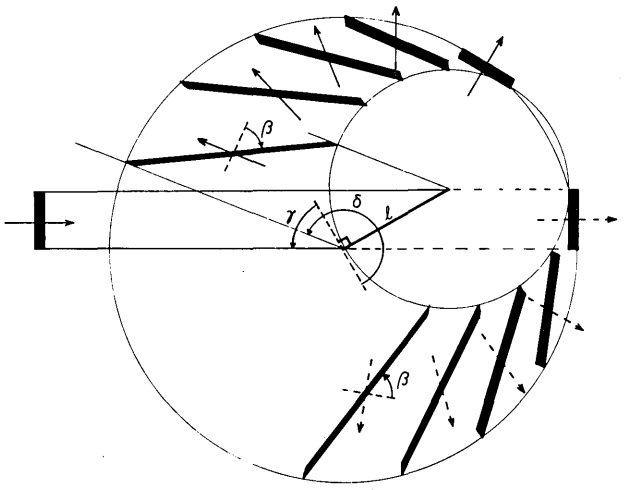


Fig. 2. Computer simulation of the pulse fronts after diffraction in the grating. The figure clearly indicates the increase of the inclination with increasing diffraction order.

to the propagation direction and the pulse front is given by the following relation [Ref. 3, Eq. (11)]:

$$\tan\beta = \frac{\sin\gamma - \sin\delta}{\cos\delta}. \tag{2}$$

Here the angle δ, which gives the propagation direction of the diffracted pulse, is given by the diffraction relation

$$d \cdot \sin\gamma - d \cdot \sin\delta = n \cdot \lambda. \tag{3}$$

When such a skew pulse front sweeps over a photographic plate with length L, as in Fig. 3, the time it takes is no longer t_N given by

$$t_N = \frac{L \cdot \sin(\theta_i)}{c} \text{ (see Fig. 1)}, \tag{4}$$

but by a longer time t_S given by

$$t_S = \frac{L}{c} \cdot \frac{\sin(\theta_i + \beta)}{\cos\beta}. \tag{5}$$

Thus we get a view-time expansion by a factor of

$$\frac{t_S}{t_N} = \frac{\sin(\theta_i + \beta)}{\sin(\theta_i) \cdot \cos\beta} \cdot \tag{6}$$

For an angle of incidence $\theta_i = 70°$ and a pulse front tilted backward by an angle β of more than 70°, the view time is increased by a factor >2.

III. Experimental Arrangements

The laser light in the experiment was delivered by a picosecond system (Fig. 3). This system consists of a mode-locked argon-ion laser pumping a dye laser (with rhodamine 6G dye). The repetition rate of the pulses from the dye laser is controlled with a cavity dumper (using diffraction in a Bragg cell). The performance of the system was checked by measuring the average power and width of the pulses, using a home-built auto correlator. Normally the system delivered pulses at 590 nm with an autocorrelation FWHM of ≈12 ps and an average power of 0.2 W. The pulses had a separation of ≈13 ns corresponding to a repetition rate of 75 MHz.

The light was spatially filtered and the divergence after the spatial filter was decreased using a 90-mm lens. Part of the light was reflected by a mirror ($M3$) for the reference beam and the rest was used to illuminate the object. The object was a plano–convex cylinder lens with a radius of curvature of 42 mm, 84 mm high. The lens was fixed to an aluminum plate that was scratched with rough sandpaper. The scratches on the aluminum plate were intended to have a curvature corresponding to the curvature of the object–beam wavefront to increase the amount of scattered light toward the photographic plate. The reference beam was diffracted at high order from a large grating (100 lines/mm, blaze ≈ 17°) to tilt the reference wavefront. Screens were used in the setup to avoid stray light from, e.g., unwanted orders from the grating. The light from the grating was reflected by a mirror ($M4$) onto the photographic plate. The photographic plate was Agfa 10E75. When measuring the exposure times in the reference and object light it was found that the optimum ratio of illumination on the photographic plate was ≈1:10 (see Ref. 1, p. 218). An exposure time of 2 or 3 min was normally sufficient.

IV. Discussion

Bartelt *et al.*[4] have demonstrated and visualized simulated pulse fronts that have been deflected by a grating and are no longer perpendicular to its direction of travel. Abramson[2] proposed that an illumination pulse front that is not perpendicular to the illumination direction could be used to compensate for relativistic distortion due to the limited speed of light. However, in this paper we demonstrate for the first time the possibility of view-time expansion in light-in-flight holography using a tilted pulse front. This can clearly be seen in Fig. 4 which shows two series of photographs through two different holograms, the second taken with the setup described above and the first with the grating exchanged with an ordinary mirror for comparison. The photographs are taken at different points along the holograms. The distances between these

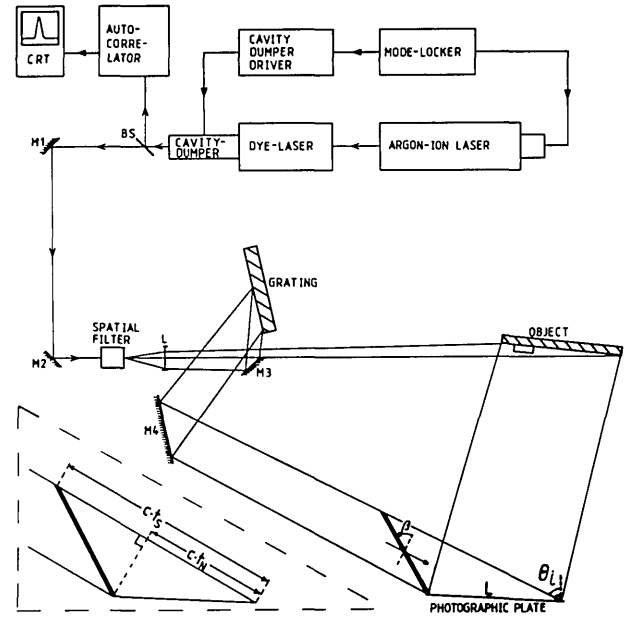


Fig. 3. Schematic experimental arrangement for light-in-flight holography using a skew reference pulse front. The reference pulse front sweeps along a plate of length L in a time t_S.

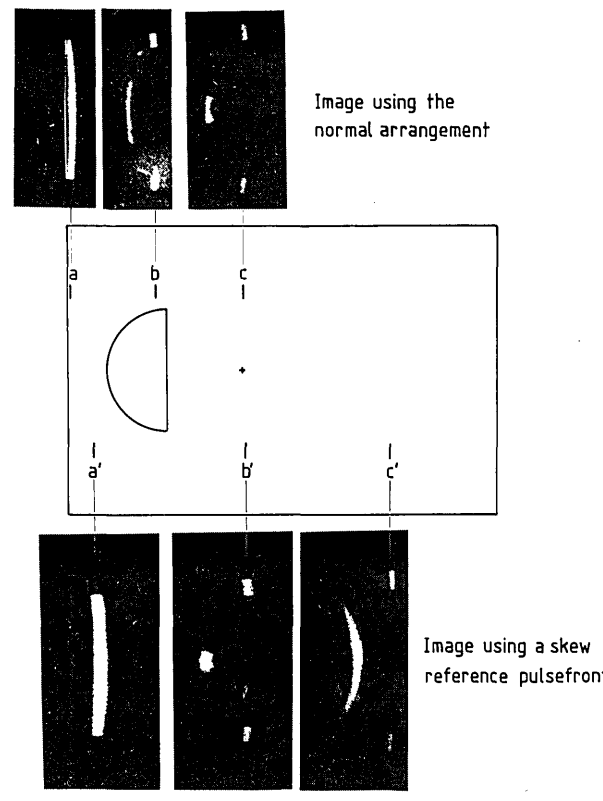


Fig. 4. Two series of three pictures each, taken at equidistant positions, show a light pulse that is focused by a lens. In the a, b, and c photos a normal LIF setup was used and in a', b', and c' the new setup, with a skew reference pulse, was employed. The effect of the expanded view time is clearly demonstrated.

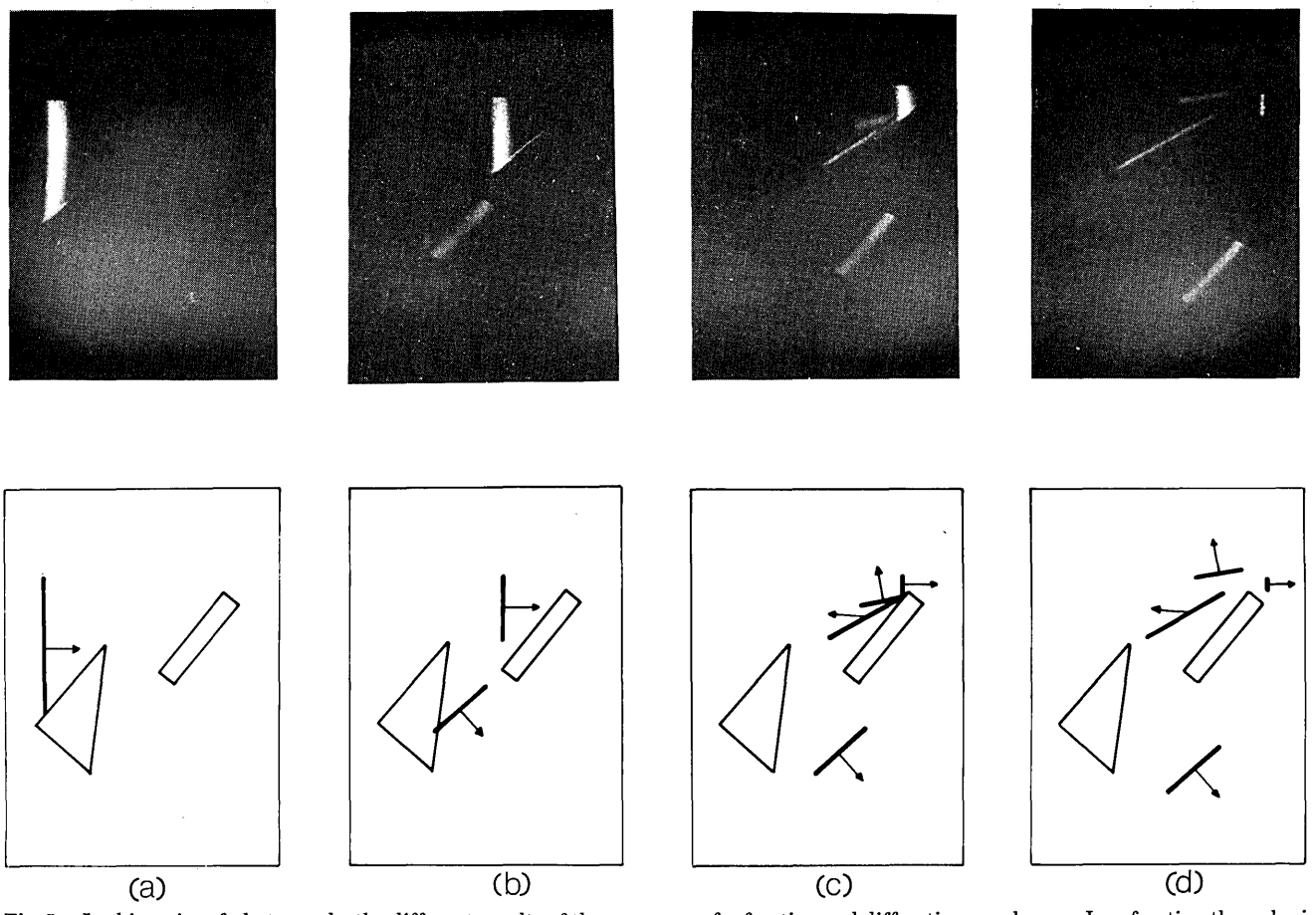


Fig. 5. In this series of photographs the different results of the processes of refraction and diffraction are shown. In refraction the pulse is only deviated but in diffraction the pulse front is also tilted at an angle to the propagation direction.

points are all equal. In Fig. 4, b' the pulse has already left the lens and is in about the same position as in c. This indicates that the pulse has traveled about twice as far in the second hologram compared with the first. Thus the view time is about two times longer in the second hologram. This is due to the longer time it takes for the tilted reference pulse front to pass the holographic plate compared to the more normal case where the pulse front is perpendicular to the propagation direction. A broadening of the pulse in the holographic recording was noted when using the tilted pulse front. This is due to the finite aperture of the observers eye (or camera aperture). For an aperture large compared to the pulse width of the laser light we get a broadening of the pulse. This broadening of the pulse compared with the pulse in normal light-in-flight approaches the view-time expansion factor.

To demonstrate the creation of a skew pulse front we made a new setup where we used a prism and a grating as objects. As reference we used a skew pulse front to get a longer view time. In Fig. 5(a) the pulse with the pulse front perpendicular to the propagation direction is just touching the prism. In Fig. 5(b) part of the pulse is transmitted by the prism and part of it has just reached the grating. The pulse front that leaves the prism is perpendicular to the propagation direction. In Figs. 5(c) and (d) a skew pulse front is diffracted by the grating together with a zero-order reflection propagating perpendicular to the pulse front. Thus this hologram clearly distinguishes between the processes of refraction and diffraction.

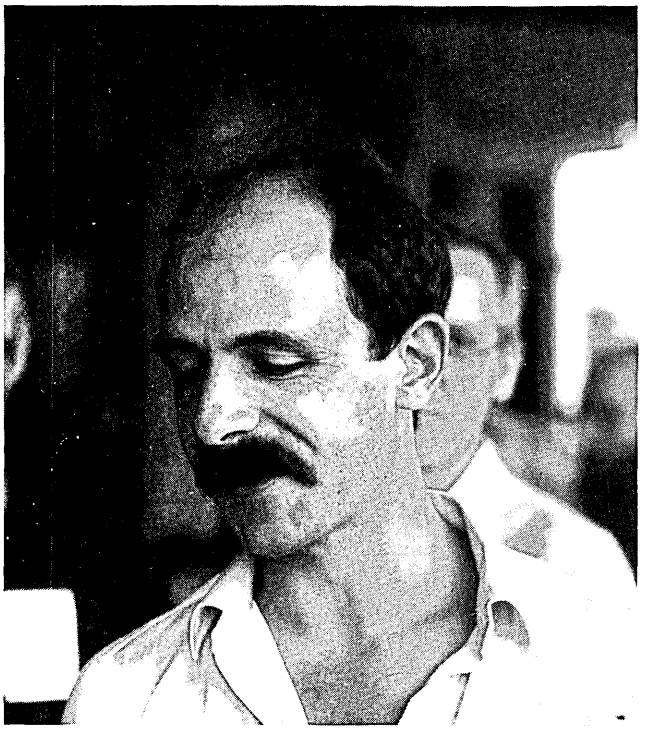
V. Conclusions

Light-in-flight holography is an experimental technique which might give a 3-D continuous moving picture of light itself. Other techniques with comparable time resolution are either more complicated or give only a 1-D image. However the observer of our hologram really sees a direct image of the studied phenomena. We foresee a large amount of possible experiments when the method is further improved. Our improvement with an expansion of the view time makes the method more versatile. The geometrical distortion of the wavefronts (see Ref. 3, Sec. VI) which appears when the observer moves along the holographic plate is slightly increased with our method. However work on another method to expand the view time and at the same time to avoid some of these geometrical distortions has been done. In these experiments we used a Fabry-Perot interferometer in the reference beam to produce a train of correlated pulses; we plan to publish this work.

The experiments described in this paper were all carried out by the authors at the Department of Physics in Lund. We especially want to thank Sune Svanberg for kindly providing us with the laser system and experimental equipment. The development of light-in-flight recording by holography has been sponsored by the Swedish Board for Technical Development whose interest and support are gratefully acknowledged.

References

1. N. Abramson, "Light-in-Flight Recording: High-Speed Holographic Motion Pictures of Ultrafast Phenomena," Appl. Opt. **22,** 215 (1983).
2. N. Abramson, "Light-in-Flight Recording. 2: Compensation for the Limited Speed of the Light Used for Observation," Appl. Opt. **23,** 1481 (1984).
3. N. Abramson, S. Petterson, and H. Bergstrom, "Light-in-Flight Recording. 5: Theory of Slowing Down the Faster-Than-Light Motion of the Light Shutter," Appl. Opt. **28,** 759 (1989).
4. H. O. Bartelt, S. K. Case, and A. W. Lohmann, "Visualization of Light Propagation," Opt. Commun. **30,** 13 (1979).



S. Schmidt-Rink of AT&T Bell Laboratories, photographed by W. J. Tomlinson, of Bellcore, at the International Conference on Optical Nonlinearity and Bistability of Semiconductors, in Berlin last August.