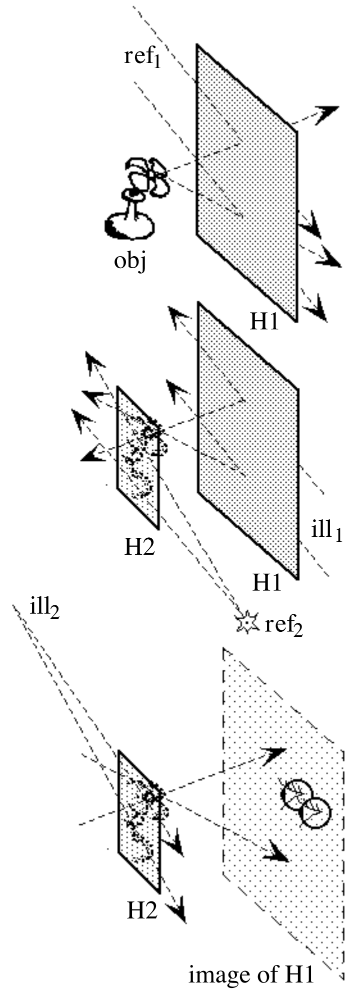
Chapter 13: Full-Aperture Transfer Holograms



The previous chapter refers to the two-step, "master-transfer," or "H1-H2" method of making holograms, in which a first hologram is used to create a real image in space, which then becomes the object for a second hologram. Normally, the image is brought as close as possible to the plane of the second hologram, the H2, so as to minimize the sensitivity of the resulting image to the source-size and color blurs usually produced by an ordinary white-light source, such as a spotlight or the sun. As such, the resulting hologram was first popularly described as an "image-plane hologram," although technically the image has no plane because it has depth! We prefer to call these "open-aperture transfers," or "full-aperture transfers" for reasons that will become clear in the next chapter. It is true that the image is usually intended to straddle the hologram plane very carefully, to minimize the maximum depth of the image.

This chapter is the story of the H2 and its optics. The previous chapter tells us almost everything we need to know about the H1, and a great deal of what we will need to know about the H2 as well. Basically, the H2 is also recorded as an off-axis transmission hologram that is later reconstructed with phase-conjugate illumination. The pseudoscopic image that results is then a depth-reversed image of a projected real image that was itself pseudoscopic, or depth-reversed. "Two pseudos make an ortho!" might be the rule—the final image reads with the correct depth compared to the original object. Thus we have produced a "right-reading" holographic image that is remarkably clear when viewed with ordinary light sources.

There are quite a few complicating factors that we have to take into account though. First, the coordinate system for the H2 is oriented differently than what we have been used to, and we have to agree upon a convention for the rotation and translation of local hologram coordinate systems in general. Second, the H2 is actually a hologram of two things at once: of the projected real image of the object, and of the H1 itself. Consideration of the second brings a new point of view to the imaging process. The exposure of the H2 is to a focused and nearly photographic-like real image, with large intensity variations over small distances, which makes the beam ratio more difficult to measure and adjust. And finally, because the H1 and H2 play very different roles in the imaging process, their exposure and processing should be separately optimized with quite different criteria in mind.

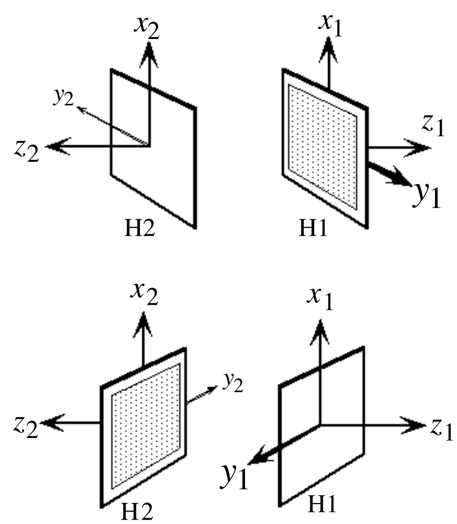
As impressive as a full-aperture transfer hologram is upon first sight, be cautioned that it is only a transitory state. The technique is of major importance for reflection holograms (serving as the H2), and we will revisit it later. But it will serve here mainly to frame the discussion in the following chapter about more advanced "rainbow" transmission holograms. There are quite a few concepts to layer on here before we are ready to go forward, and full-aperture transfers are wonderful tools for learning.

Further discussion of H1-H2 technique:

The creation of images that came up to and through the hologram plane was a revolutionary step when introduced in 1966 by Rotz and Friesem, of the Univ. of Michigan group[1]. Within a few years, it became the technique of choice for most display holograms[2]. Although there were several attempts to produce image-plane holograms in a single optical step, by the use of large lenses and mirrors for example, the two-step hologram technique has come to be the generally accepted practice. It is a technique that requires an extra holographic step, which means separate setups for mastering and transferring, usually by tearing down the first and replacing it with the second. This makes the usual "cut and try" methods of holography impractical, as re-shooting the master becomes more and more time-consuming (except for those few with the luxury of two tables, lasers, and sets of gear!). The use of a few mathematical calculations makes it much easier to get it right, or nearly right, on the very first try, and the recognition of the utility of shop-math-based holography followed the emergence of these two-step techniques. They allow a degree of precision in "previsualization" that is necessary for efficient work, so that the holographer can judge with some confidence what is likely to appear in the final image.

At about the same time, it became generally realized that the illumination for holograms was going to have to come from above, as it does for most other display media, if holography was to become competitive. Looking into the beam of a side-lit hologram can be an uncomfortable, or at least worrying, experience. And rainbow holograms are going to absolutely require vertically-inclined (usually overhead) illumination, so here is where we start to deal with it in earnest. Although we can blithely sketch "underhead" reference beams to result in overhead illumination beams, it is difficult to bring such beams up through the solid tables we usually work with. Many holographers have come up with clever multi-mirror periscope schemes to allow vertically-inclined reference beams, but it is best to avoid mirrors in reference beams whenever possible. The easy way out is simply to turn everything on its side! This complicates things a bit when it comes time to describe the direction or location of this or that item, as the final hologram's frame of reference is turned 90° to the laser table's frame of reference. We will ignore this particular practical issue for most of this chapter's discussion, and will continue to sketch as though we had transparent tables to work upon.

The holo-centric coordinate system:



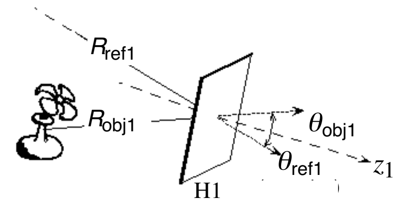
Up to now, the holograms have (very conveniently) been facing straight along the "minus z" direction, so that angles could be measured in the usual way: a positive angle is one that a clockwise rotation would bring to the z-axis that emerges from the back of the hologram. Now we will have to construct a small traveling coordinate system for each hologram, and our convention will be that the z_i-axis will be sticking out of the "back" of the i-th hologram, no matter what its orientation will be! And, we will define the "front" of the hologram as the face that receives the object-beam exposure (the reference beam also hits the "front" of the hologram, for transmission holograms). As a gesture of friendship, we will continue to show the master hologram, the H1, as facing in the general direction of "minus z, so that object and reference beam angles will usually be between plus and minus π (±180°) in the global coordinate system (they are always between plus and minus π in the holo-centric coordinate system). The transfer hologram, the H2, on the other hand, will generally be facing in the opposite direction, so that its "plus z_i" direction is roughly in the <u>minus</u> global-z direction. Assuming that the local coordinate system is "glued" to the i-th plate, there are two ways to go from what we have been using to what we need for the H2—by rotating "head over heels" with the horizontal y-axis used as an "axle," or by spinning around the vertical x-axis. We will choose the second or "spinning" method, so that the x_i-axis of the H2 will stay roughly vertical but the y_i-axis will now poke <u>into</u> the page, as shown in the approximately-isometric marginal sketches. For the transfer hologram, the H2, positive angles will be those for which a *counter-clockwise* rotation brings them into the z_i-axis.

While angles may be a little difficult to keep track of, distances and curvatures are no different than before. A diverging wave will have a positive radius of curvature whether it is traveling from left to right, or from right to left (or from top to bottom, of course). And a negative radius of curvature will denote a converging wave, whatever its angle of propagation.

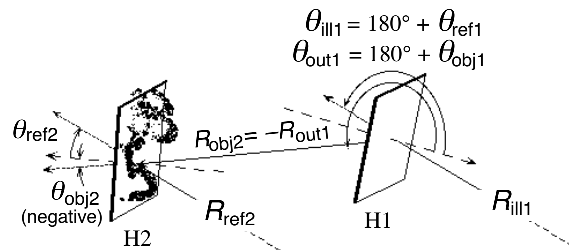
This can get a little confusing for spatially-challenged thinkers. From time to time it is helpful to think of yourself as being in the center of the hologram, in order to see what it sees and to judge what kind of fringes and optical behavior might be produced. Now, you just have to add a spear sticking out of your back, denoting the positive z_i axis, with your right arm sticking straight up to be in the direction of the positive x_i axis, and your left arm pointed out sideways to indicate the positive y_i axis (a good old-fashioned right-handed coordinate system). Now just pivot around and shuffle about (like practicing Latin dance steps in your mind) to take on the orientations of the various plates in a two- or even three-step system, and you can readily gauge what angles and radii to plug into the three equations that we will continue to use.

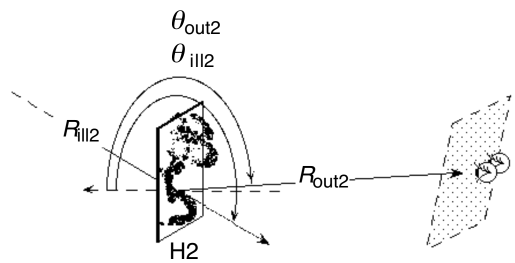
Example:

As an exercise, let's just walk through a typical full-aperture geometry, as sketched alongside. In the first exposure, or "mastering" step, the object beam angle (θ_{obj1}) is positive because we are deliberately tipping the H1 back so as to make the interference fringes be perpendicular to the plate (for easier processing design). The reference beam is from "overhead" (in the hologram frame), and has a negative angle (θ_{ref1}). Both the object beam and reference beam are diverging in this example (R_{obj1} and R_{ref1} are positive).



In the second exposure, or "transfer" step, the H1 is illuminated with a beam in the direction opposite to that of its reference beam ($\theta_{ill1} = 180°+\theta_{ref1}$), and the output beam is traveling in the direction opposite to that of the object beam ($\theta_{out1} = 180°+\theta_{obj1}$, assuming no change of wavelength between exposure and transfer). The output beam is a converging wave, focused at the distance of the H2 to produce an image straddling the hologram plane ($-R_{out1}$ = S (separation) = R_{obj2}). Both the reference and illumination beams for H1 are diverging, so that the output radius is larger than the object radius (though still negative), so that the image is farther away and magnified.





In the final "viewing" step, again assuming the same wavelength is used, the H2 illumination is angled in the direction opposite to that of the reference beam ($\theta_{ill2} = 180°+\theta_{ref2}$), and the output beam is traveling in the direction opposite to that of the H2's object beam ($\theta_{out2} = 180°+\theta_{obj2}$). Because both the reference and illumination beams are diverging, the output wavefront's radius of curvature is again larger than the exposing wavefront's radius of curvature, and the real image of the H1 is formed farther from the H2 than the H1 was during exposure.

At this point we have not yet discussed *astigmatic* focusing, although both H1 and H2 are clearly not enjoying perfect phase-conjugate illumination, and their output beams will be markedly astigmatic. For the purposes of side-to-side parallax and triangulation by the eyes, it is the horizontal or *y*-focus that matters, and the "$1/R$" equation is the relevant focusing law for placing the apparent distance of the image projected by the H1 exactly at the H2 plane. However, it is the <u>vertical</u> parallax between the image and the H2 that allows blur under white-light or extended-source illumination, so that the vertical focus or "$\cos^2\theta$" relationship is the relevant equation for the H1, if image sharpness is the main issue[3]. The calculations are straightforward, if a little tedious to do by hand (as you will doubtless discover from the homework exercises).

Separate optimization of the H1 and H2:

This is a good time at which to mention that the H1 and H2 will typically be very different types of holograms, as the exposure and processing of each is optimized for the characteristics most important at each step. In the teaching lab we are likely to use the same techniques for both, but in commercial practice they are usually very different. A general statement of the different roles is: the H2 needs to be bright above all else, and the H1 needs to produce a "clean" image above all else. Let's discuss the issues for the H1 or "master" hologram first.

master hologram issues:

high contrast vs. brightness: The ratio of intensity between the whites and blacks in a glossy paper print is limited to about 50:1, and is much less than that for television images (and much higher for projected slides and movies). Reaching a 50:1 matte white to shadow area ratio in a holographic image is really quite difficult. It requires using a high beam ratio, between 30 and 50 typically, to keep intermodulation noise low. Even though this produces a fairly dim image, the low scattered light is more important. The hologram may also be exposed and processed without bleaching, as it is widely believed that bleaching lowers the contrast and degrades the archival stability of the hologram (I disagree with both contentions). And the master is typically recorded on a glass plate for flatness and durability, and used while index-matched to reduce scatter by any surface relief in the emulsion. The details of optimizing the contrast and brightness of a hologram image require a careful study of exposure, beam ratio, and processing effects for each recording material used. Phillips *et al.* report conducting several thousands of tests during the development of his reflection hologram processing techniques, for example[4].

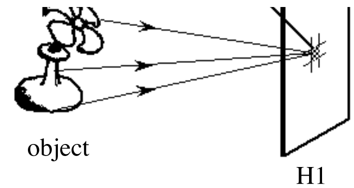
split-angle recording: Obtaining clean and undistorted real image projections requires that the angles of the fringes recorded in the thickness of the hologram do not change between exposure and reconstruction. Most processing chemistries change the emulsion thickness by several percent (up to 20%, in principle), which would significantly change the angle of any fringes that are not vertical to the emulsion surface. Therefore, master holograms are usually tilted so that their perpendicular bisects the angle between the reference beam and the center of the object, to make the fringes as "vertical" as possible. In addition, "splitting the angle" makes the reconstruction free of astigmatism, if the illumination beam cannot be a perfect conjugate of the reference beam. However, this is not the configuration that minimizes "coma" in the image (for which the plate should be almost perpendicular to the object), and that may be a more important consideration , especially for rainbow holograms. It is easy to tell when the plate is bisecting the reference-object beam angle, by the way: the reference beam will reflect onto the object!

transfer hologram issues:

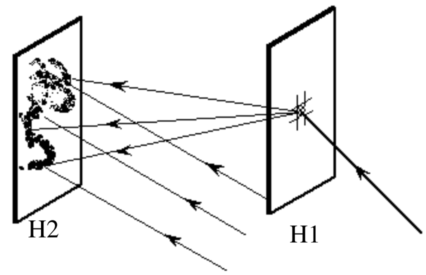
The final hologram, on the other hand, has almost the opposite qualities as desiderata. The image must be maximally bright, because without adequate luminance a holographic display is pointless. The contrast is usually degraded more by external light leaks than by intermodulation noise (although these can often be overcome by careful masking). Thus the hologram is usually exposed at a low beam ratio, and almost always bleached. It may or may not be laminated, which provides index matching as well as protection from the elements. The hologram must typically hang vertically, in order to be as inconspicuous as possible (and as much like a photograph as possible), so that tilted fringes are inevitable. Avoiding shrinkage effects means pre-compensating for them, or using only non-shrinking processing chemistries. Also, to reduce the cost, transfers are often recorded on flexible film base materials, which require care to keep acceptably flat.

We will revisit many of these issues when we spend more time talking about processing chemistries and techniques.

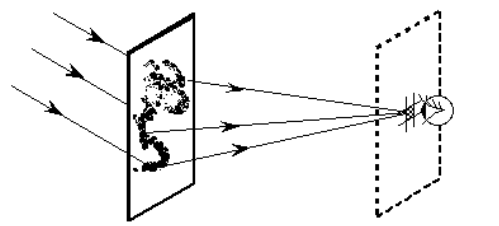
Another point of view: H1 as multi-perspective projector:



"All problems in optics are straightforward, if you look at them the right way," says the old maxim, and there usually are several points of view that can be tried for any particular question. In the present case, we have been thinking of the H2 as recording a hologram of the real image projected by the H1, just as though it were any ordinary object that happened to be able to straddle the hologram plane. And that point of view explains a great deal of what happens when we make a hologram this way. In particular, if we examine the color blur produced in white light (as seen well away from the top and bottom of the view zone), the blur of a point image produced by a master hologram is the same as the blur of a point image produced by an actual object.



However, at the same time, the H2 is also making a hologram of the H1, and later projecting an image of the H1 into space, where it defines a *viewing zone* or *view window* for the final 3-D image. The H2 will record images of everything it sees, of course, but it is helpful to distinguish between the imaging of the object and imaging of the view-zone window as separate events.



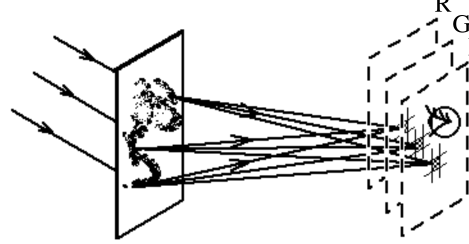
Another useful "mental model" of the hologram's behavior is to consider the H1 to be acting like an array of small imaging systems: first as cameras recording perspective views, and then as projectors beaming those perspective images back into space. That is, every small area or patch of the hologram (perhaps three millimeters on a side, or somewhere between one and six) records a single perspective view of the object scene, as seen from the location of that particular patch. When the hologram is illuminated in phase conjugation, each patch projects its perspective view back in the direction it came from. One way of observing this in a real hologram is to probe small areas of the H1 with an undiverged laser beam, and note the perspective that is projected onto a white card at the intended location of the H2, and then to watch how this image changes as the probe beam is moved around the H1. The "mental model" of the H1 as an array of cameras and turned-back projectors becomes a powerful one when thinking about holograms transmitting images when phase conjugation is used, especially as things become more and more complicated.

Where the many projected perspective views overlap, a three-dimensional real image is formed from their sum; but let's consider the H2 instead to be making a recording of the sets of beams from only one of the H1 patches (as in the sketch—normally all of the patches would be exposed at the same time). Now, when the exposed and processed H2 is illuminated in turn by the phase conjugate of its reference beam, it sends back to the real image of each H1 patch the set of beams carrying the perspective view originally recorded from that location. An eye placed at that location sees that perspective view, and only that perspective view. As soon as the eye moves away from that patch, the image goes dark. When the eye moves to the location of the next patch, or rather the next real image of a patch, it sees a different perspective view of the scene (of course we will fill in the patches so that the view never goes dark).

Anything that disturbs the location of the real image of the H1 will change the location of the patches as a group, and thus will change (in a systematic way) the view that the eye sees at any particular location. This will look like a rotation of the object if it happens while the eye is fixed (more accurately, a shearing motion around the central plane of the hologram). That is, changing the illumination wavelength, divergence, or angle won't blur the image, it will just change its orientation and perhaps distort it a bit.

color blur:

One way of thinking about color blur, in terms of this new model, is to think instead of how the image of the H1 is changed by changing the wavelength of the H2's overhead illumination. If the wavelength is changed from red to green to blue, the image of the H1 (which we will usually call the "viewing zone") moves outward and, more importantly, downward (being rotated less radically). Thus, if the H2 is illuminated in blue light, the eye will see through the top of the image of the H1 hologram, and see the "high" perspective view of the object scene. More of the top of the object will be seen then, and only in blue light. Or, if the H2 is illuminated with red light, the eye will see through the bottom of the image of the H1 hologram, and see the "low" perspective of the object scene. Thus more of the bottom of the scene will be seen in red light.




BLUE


GREEN


RED


BLUE FRINGE AT TOP
RED FRINGE AT BOTTOM
(as seen against a black background)

If the hologram is now illuminated with "white" light, which presents red + green + blue simultaneously, all three differently-colored perspectives will be seen simultaneously. The various colored images will be the same and in register only where the 3-D image lies in the H2 plane. For image components out of that plane, the eye will see different perspective views in different colors, and where those views don't overlap in perfect registration, the eye will see "color blur." Because the differences between the perspectives are mainly in their vertical rotation, the color fringes appear mainly at the top and bottom of the image. Thinking of color blur as caused by a mixing of vertically-differing perspectives of various colors is often a more fruitful approach than our previous "spectral-blur of the scene image" model. It also makes it clear why the image seen from the center of the view zone can be so "achromatic" or neutral-toned, which is attractive to many artists.

View-zone edge effects:

A characteristic of two-step H1-H2 holograms is that they present a viewing window that appears to hang in front of the hologram (assuming monochromatic illumination, or a reflection-mode hologram). The viewer's eyes must be inside the window area in order to see anything. If the view is at the same distance as the window, or viewing zone, the image "snaps" off as she or he moves across the edge of the zone, either horizontally or vertically. If the viewer stands back considerably further, she or he can see the edge of the view zone move across the image in a direction opposite to the viewer's motion, and perhaps perceive the edge as literally hanging in space like an open window. The wider the master plate, the H1, the wider the view zone will be, and the closer the H1 is to the H2, the wider the viewing angle the view zone width will allow. For full-aperture transfers, it is common to place the H1 as close to the object, and to the H2 afterwards, as is possible. However, for rainbow holograms it is necessary for the H1 to be at a carefully specified distance, usually much further away. Deliberately limiting the viewing angle increases the brightness of the image, as the same amount of light from the hologram (the illuminance multiplied by the diffraction efficiency) is concentrated into a narrower beam.

If a full-aperture transfer hologram is illuminated with white light, some interesting things happen as the viewer's eyes move vertically across the top or bottom of the view zone (assuming vertically-inclined illumination). Moving upwards, for example, we see that the eyes move off of the blue-light view zone first, and then the green, so that an image in only red light is remains, and is fairly sharp. That is, the width of the visible light spectrum is limited by the hologram geometry (the H1 edge) on the green side, and by the end of the eye's spectral sensitivity (the visibility curve) on the infra-red side. Conversely, if the eyes move off of the bottom of the view zone, the image becomes deep blue in color, and again fairly sharp (although things never look quite as sharp in blue light as in red); the visible spectrum width is limited by green-side spectral cutoff by the H1 edge and by the ultraviolet end of spectral sensitivity of the eye.

Conclusions:

Full-aperture transfer holograms, or image-plane holograms, have played an important part in the history of display holography, and are still important for reflection holograms. They provide vertical and horizontal parallax, and their images can project far into the viewer's space for dramatic effects. Although they are much less vulnerable to spectral and source-size blur than deep virtual-image holograms, their depth of field is limited to something less than 25 mm (one inch) with white-light illumination. The model of a master hologram, or H1, as an array of cameras and turned-around projectors is a valuable tool for thinking about these and other display holograms, as we move along to rainbow holograms and holographic stereograms.

References:

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