The Problems of Holographic Interferometry

by K. A. Stetson

ABSTRACT—The history of holographic interferometry is one of problems. It has progressed from a novel discovery to a recognized technology only by the systematic pursuit of explanations for the puzzling phenomena it presents: unusual fringe patterns, fringe localization phenomena and bizarre fringe parallax. How to use the fringes to find three-dimensional deformation patterns is also a problem. Furthermore, the problem of how to handle high-volume testing spurred the evolution from photographic plates to flexible roll film for all electronic media. Finally, the use of CCD television cameras and digital video processing has made phase-step interferometry the dominant method of fringe analysis but presents a major problem in the form of the phase-unwrapping quandary. This paper will attempt to trace the history of this technology in terms of the problems it has presented and their solutions.

KEY WORDS—Interferometry, holography, fringe analysis, vibration analysis, deformation analysis

Holographic interferometry has been the source of many interesting topics for research and development over its 35-year history and continues to provide challenges even now. To understand these problems, it is necessary to know what holographic interferometry is and how it revolutionized the field of interferometry, which in turn requires some acquaintance with interferometry itself and the state of the art in 1964. As with any radical development in a classical field of science, it was not obvious how things would progress. Much of what happened could not have been predicted in the mid-1960s, and it took decades of problem solving and technical development to bring the field to the point at which it is today. I have occasionally been asked whether Robert Powell and I foresaw what this field would become back in 1964 when we viewed the first holographic interferograms, and my answer has always been no. We knew it would be big and far reaching, but we could not foresee the breadth and scope that other technologies would bring to it. In this paper, I intend to discuss the most significant problems of holographic interferometry and their solutions in order to show how and why it has grown the way it has.

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Discovery

Interferometry, before the hologram, was applied almost exclusively to lenses and mirror-like surfaces. There were many remarkable applications to mechanics in addition to the more common applications to optical fabrication and physical measurement, but the surfaces involved in any of these measurements had to be polished optically. Interferometry exploits the wave nature of light. If two beams of light are combined properly so that their wave fronts match and they appear to come from the same optical source, it is possible for them to interfere in a manner analogous to sound waves or water waves, and the difference is mainly one of scale. Light travels at a speed of $3 \times 10^8$ m/s and consists of electromagnetic oscillations in the range of $6 \times 10^{14}$ Hz. The distance between wave crests in a light beam is, therefore, in the range of $0.5 \times 10^{-6}$ m. Also, before the laser, light sources were the optical equivalent of noise generators, and that is still the best description of most light sources from sunlight to the incandescent lamp. Photons of light are little wave packets of energy emitted by molecules as they expel energy they have absorbed from heat, electrical or other means of stimulation. Most light we see comes from billions of molecules randomly absorbing and expelling energy, rather like an audience clapping after a concert. It is only under special conditions that these noisy signals can be matched well enough to create interference effects. The need for mirror-like surfaces and smooth lenslike objects came from these critical requirements.

Even without the hologram, the laser created a revolution in interferometry. In a laser, the expulsion of energy from molecules becomes coordinated. Light is made to pass back and forth through the same material into which energy is being injected, and, as the wave crests pass through, they stimulate the molecules to emit their energy in synch, somewhat like an audience that starts to clap in unison. The light from a laser is much purer in color than light from a lamp and appears to come from a single point source. Because the wave fronts all appear to be connected to one another in this manner, the light is called coherent. With ordinary light, which has very little coherence, interference effects are the exception. One sees them in oil slicks, where a very thin layer of oil spreads out over a smooth water surface; they can also be seen in the reflection of sunlight off a finely ground metal surface. But with laser light, interference effects are the rule.

Some of the first commercial lasers were bought by the Radar Laboratory of the Institute of Science and Technology at the University of Michigan and used for optical processing
of coherent side-looking radar data; soon after, they were used for experiments on recording holograms. The first holograms were made with light beams that passed through photographic transparencies; then, as confidence in the coherence of this light grew, holograms were made with light diffused by a ground glass plate and passed through a transparency. From there it was a short step to recording holograms of the light reflected by a three-dimensional object, and with this Denis Gabor’s obscure discovery of 1949 vaulted into world-wide popularity. The idea of a photograph that could capture the complete three-dimensional nature of light reflecting off an object captured the imagination of a generation of optical physicists.

In the 1960s, holograms were recorded on glass plates coated with photographic emulsions. Light from a laser was split into two beams: one illuminated an object and the other provided a reference beam. The photographic plate was exposed to the mixture of light reflected by the object and the reference beam. Because of the extremely high coherence of the laser light, these two beams interfered to form a fine grating-like pattern that the photographic emulsion could record. After the plate was developed, it was illuminated by a replica of the reference beam, and it would diffract part of that beam into a replica of the light reflected from the object. There was no visual way of distinguishing the hologram reconstruction from the original object. Holograms were like magic looking glasses in which one could see things that were not there.

I have described elsewhere the sequence of events that led Powell and me to explore the periodic coherence of the light from the old helium-neon lasers we were using, and how that led us to explore the nature of holograms recorded of laser beams that had more than one transverse mode. It was here that our magic looking glass showed us something that was not there: an interference fringe between the two transverse modes of the laser that was not there in the actual laser beam. The only explanation was that the hologram had some unforeseen ability to make light beams coherent that were not originally coherent. From there, we made double exposure holograms that showed interference between light fields that had never existed at the same time and then time-average holograms of vibrating objects that showed interference fringes that defined the shapes of vibration patterns. Thus, holographic interferometry was born, and suddenly interferometric measurements could be made on nonmirror surfaces, that is, on structures of ordinary engineering interest.

Early Problems

Vibration Fringes

The first problem of holographic interferometry was to describe the fringes seen on vibrating objects. With conventional interferometry, fringe patterns were sinusoidal brightness variations. Even with multiple beam interference, as observed in a Fabry-Perot interferometer, the fringe patterns could be described by a series of sine or cosine functions. The fringes seen in the hologram reconstruction of a vibrating object were clearly different, however. The vibration nodes appeared quite bright, but fringes appeared in the antinodal regions whose brightness decreased with vibration amplitude. The fringes seemed to connect regions of common vibration amplitude and could be read like a topographical map. A search through the archives revealed an article by Osterberg on the use of interferometry to measure vibration. From his analysis, it was clear that the fringes must follow a zero-order Bessel function of the first kind, that is, \( J_0(\Omega) \), where \( \Omega \) is a function of the vibration amplitude that came to be called a fringe locus function. Some geometrical analysis soon showed that the function \( \Omega \) must be given by

\[
\Omega = (K_2 - K_1) \cdot L = K \cdot L, \tag{1}
\]

where \( K_2 \) and \( K_1 \) are propagation vectors for the light traveling from the object to the observer and from the illumination to the object, respectively, and \( L \) is the vectorial displacement of the object. The difference vector, \( K_2 - K_1 \), became known as the sensitivity vector, \( K \). The magnitudes of the propagation vectors are \( 2\pi/\lambda \), where \( \lambda \) is the wavelength of light.

Characteristic Fringe Functions

One of the first major insights into the fringes of holographic interferometry came from Adam Kozma in an internal memorandum. Although he never published this work, I included it in an article on the analysis of nonsinusoidal vibrations, with an appropriate citation. The analysis goes as follows. The function that generates the fringes in holographic interferometry may be written as

\[
M(\Omega) = (1/T) \int_0^T \exp[i\Omega f(t)] dt, \tag{2}
\]

where \( T \) is the hologram exposure time, \( t \) is time, \( f(t) \) is the function describing the object motion and \( M(\Omega) \) is the fringe function. If we assume that \( f(t) \) is stationary and ergodic in a statistical sense, or satisfies analogous conditions if it is deterministic, this equation may be rewritten using its probability density function \( p(f) \) as

\[
M(\Omega) = \int_{-\infty}^{+\infty} p(f) \exp[i\Omega f] df = F(p(f)), \tag{3}
\]

where \( F(p(f)) \) indicates the Fourier transform of \( p(f) \) with respect to \( \Omega \). In statistics, the function \( M \) thus defined is called the characteristic function of a probability distribution function, and for that reason fringe functions in holographic interferometry are generally called characteristic fringe functions. The main insight is that fringe functions are Fourier transforms of the density distributions of the generating object motion and that the fringes depend not on the exact path followed by the object but on how long it spends in each position it occupies. Further consideration led to the result that independent motions of the object generate independent fringe functions whose product forms the resultant fringe function.3

Fringe Localization

Understanding fringe localization was one of the first major problems of holographic interferometry. Powell and I noticed in our earliest experiments fringes that did not always focus at the surface of the object being reconstructed. Although localized fringes were well known in what was called broad-source interferometry, the theory developed there was not well suited to the geometries of holographic interferometry. Although two early publications purported to solve this problem for holographic interferometry,4,5 their results could not be called insightful. Thus, many people took up the