Hologram Interferometry And Speckle Metrology:

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As I write this article, it is autumn, 1979. Fifteen years ago, at this time of the year, Robert L. Powell and I performed some experiments at the Institute of Science and Technology (as it then was) at the University of Michigan, in the Radar and Optics Laboratory under Emmett Leith. Our contract objective was to study holograms for their potential in aerial photography; however, in practice we were trying to find out why, of all the holograms recorded of a three dimensional object, one was excellent and the rest were poor. In the course of our experiments we noticed certain characteristics of "bad" holograms and sought to investigate these defects. The result was the discovery of hologram interferometry.

It is sobering to realize that students now graduating with masters' degrees were in the middle of elementry school then. A generation of students in optics is growing up unaware of the restrictions that once encumbered the field of interferometry. In many curricula, holographic interferograms are made as routine laboratory experiments.

Similarly, ten years ago last July, John Leendertz, then a student at the University of Technology in Loughborough, England, presented a paper at a congress of the International Commission for Optics in Reading. He showed how to perform interferometry on diffusely reflecting objects by means of laser speckles, i.e., without even the benefit of holograms. Whether or not it can be said that hologram interferometry created the incentive for the discovery of speckle interferometry and speckle photography, there is no doubt but that it greatly aided its development. Speckle techniques of metrology are also making their way into curricula, and both are becoming widely used as measuring tools for structural deformations.

Yet, within the field of optics, hologram interferometry and speckle metrology suffer a social disadvantage. They generally do not solve problems in optics but instead find their major applications in mechanics. Thus it is not surprising, perhaps, that none of the major advances in these technologies have come from either of the two centers for research in optics in this country. The advances have come in largest part from research centers in mechanics. For this reason it may be difficult for the general optics community either to evaluate the progress of technology in these areas or to foresee the important areas for future work. From the point of view of one who has the good fortune of still being able to work in this area, especially after having done so for the last 15 years, I should like to beg the indulgence of the readers to give a personal, and no doubt highly prejudiced, survey of what has been accomplished and what remains to be done.

HOLOGRAM INTERFEROMETRY: THE EARLY YEARS

I would say, broadly speaking, that during the first five years of hologram interferometry the major issue was the interpretation of fringe patterns in three-dimensional space. Although this period also saw the development of most of the major techniques of hologram interferometry: double exposures, multiple exposures, time-

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average exposures, beam modulation, stroboscopic exposures, multiple illumination and observation directions, fringe parallax and localization; the question that pervaded much of this work was: What is the connection between object motions and the behavior of fringes? Furthermore, the object motion had two facets, its temporal nature and its geometrical nature. In general, these two facets affected quite different aspects of the fringes. The temporal motion of the object affected the characteristic function whose zeros defined the fringes. Therefore, double exposures would generate cosine fringes, sinusoidal vibrations during time-average exposures would generate zero-order Bessel function fringes, etc. The geometric nature of the object motion affected the actual form of the fringes, the fringe loci, and fringe localization.

By 1970, published material was available in the journal literature that predicted accurately the fringe function that virtually any object motion might generate, as well as the form and localization of the fringes. Methods were also well established to extract vectorial object displacements from the fringes, their parallax, and their localization. The chief difficulties with these fringe analyses, however, lay in the amount of mathematics used in their derivations and the amount of calculation required in their applications. Thus the search to find simpler ways of describing fringes in hologram interferometry has continued. This search has led to a large volume of work on fringe analysis that has underscored a basic problem in this field. If a theory is simple enough to be easily understood, it is not general enough to be of practical value in real engineering problems. If a theory is general enough to be useful in complicated problems, it will involve considerable mathematical derivation.

For many, this difficulty could only be resolved by the rejection of hologram interferometry as "too complicated." This meant a return to previously used methods of mechanical analysis or a search for other optical methods that would not present such problems. It was certainly from this point of view that many looked at the emerging field of speckle interferometry and photography.

THE MIDDLE YEARS OF HOLOGRAPHY—THE EARLY YEARS OF SPECKLE

The first five years of the 1970's saw some interesting developments in hologram interferometry and in the new field of speckle metrology. A key element in the development of both was the strong participation of mechanical engineers in these fields. These people were not mainly interested in the prediction and description of optical phenomena, e.g., fringe formation and localization, but were interested instead in the mechanical deformation of the objects involved. Thus, in both fields, interest began to center on the measurement of strain. In the new speckle techniques this interest was particularly strong because the techniques lent themselves to measurement of object displacement transverse to the direction of observation. For object surfaces that could be observed normally, this made strain measurement quite simple.

In hologram interferometry, the major advance of this half decade was the idea of using redundant fringe observation to reduce the effect of data errors in the computation of object displacements. The beginnings of holography of rotating objects also date from this period, as does the use of holographically recorded vibration modes in vibration analysis. More important, however, fringe subtraction methods, both numerical and through double-illumination beams, were introduced to aid in isolating displacements transverse to the observing direction. As a direct result of these developments, computers began to be used to process fringe data for the extraction of displacements and strain.

During the first five years of speckle metrology, a wide variety of techniques emerged. The first of these techniques were described as speckle interferometry and were directly analogous to classical interferometry in that they made use of the interference between two or more randomly speckled fields. The detection of this random interference was based upon the cyclic repetition of the combined speckle pattern every 2π phase change between the fields. Whereas these methods had interferometric sensitivity, the methods of speckle photography, which followed soon after, greatly extended the range of displacement measurement. Speckle photography made use of the displacements of speckles in the image plane of a standard optical system, and it conveniently filled a gap between holographic interferometry and moiré interferometry. These methods were soon extended to the measurement of vibration, surface tilt, and bending.

THE LAST HALF DECADE—A METROLOGICAL PARTNERSHIP

After the establishment of speckle techniques, a division of preference developed between metrology by holography or by speckles. Many enthusiastically favored the speckle technology because it freed them from concern about fringe localization and other problems of making holograms. This zeal even gave rise to such wishful misstatements as: Hologram interferometry measures displacement, whereas speckle interferometry measures strain. In the face of this, it is not surprising that the last half decade of speckle metrology has seen a considerable interest in the pitfalls and limitations inherent in these techniques. These range from lens aberrations and film characteristics to the simple problem of defocusing, from the influence of unwanted axial motions to loss of speckle correlation because of surface tilts.

In hologram interferometry, the last half decade has seen the flowering of matrix methods and tensor calculus in the analysis of fringes. This gave such an insight into the relationship between object deformations and the fringes they cause that it became possible for the first time to devise methods of true strain analysis. Also during this period, statistical analysis began to be applied to hologram interferometry to estimate the effect of data errors on displacement and strain analyses. But perhaps one of the most significant developments was the introduction of heterodyne interferometry into holography to improve fringe detection to one part in 10^3. As a consequence, hologram interferometry is beginning to show its true potential in structural metrology.

In speckle metrology, attention has come to be focused not only on the displacements of speckles in a single focal plane but also on their displacements in the three-dimensional space that surrounds the image of an object. A curious irony has attended the analyses of these displacements. The rigorous description of these speckle displacements has required mathematical analyses not only as complicated as that of holography but also in many ways exactly equivalent. Quite logically, regions of fringe localization in hologram interferometry have been shown to be equivalent to regions of zero speckle translation, or speckle boiling, as it is referred to in some papers. One of the primary benefits of these mathematical analyses has been the carrying over of methods of holographic strain analysis into speckle metrology.

Finally, in the field of speckle metrology, the increasing demand for rapid and large-scale acquisition of data, coupled with the need for more processing of these data, is stimulating the development of automatic fringe-reading equipment that can be integrated with data-processing systems. In this sense, both speckle metrology and hologram interferometry have come to the same bay: they depend on data acquisition and processing for application to real-world problems.

THE FUTURE—A MEETING BETWEEN OPTICS AND MECHANICS

It seems to me that the future of hologram interferometry and speckle metrology will depend in large measure on the quality of interaction between the fields of optics and mechanics. It seems unlikely that these measurement technologies will yield instruments of metrology in black boxes, i.e., devices whose internal functions are unknown to the user. The future seems far more likely to resemble the present, in which systems using these technologies are designed and operated by people educated in both optics and mechanics.

It is in recognition of this projection that the Optical Society of America is sponsoring a Topical Meeting on Hologram Interferometry and Speckle Metrology. It is to be held on June 2-4, 1980, at the Sea Crest Hotel, North Falmouth, Cape Cod, Massachusetts. This date and location place it in conjunction with the 4th International Congress on Experimental Mechanics of the Society for Experimental Stress Analysis to be held the previous week in Boston. It is my hope that the format of an OSA topical meeting will provide a stimulating atmosphere for what is the first major scientific meeting in the country on these topics.

Yet, technologically, what is the future of these fields? I would guess that what is most likely to happen is that which we are least likely to foresee; however, with that disclaimer I shall try to make some predictions. At present, there is not really an industry involving strain measurement by either holography or speckle in the sense that *is* an industry centered on strain gauges. Similarly, there are a number of systems commercially available for vibration analysis by conventional technology, whereas there is no comparable industry based on holography or speckle. There are many good reasons why this should change (these are the reasons why so much research continues in these fields), but there are also many obstacles. A photographic material with high sensitivity and rapid, dry processing would be desirable in this technology, but its absence is not really the obstacle that many imagine it is. The hologram or specklegram is still really the ante to the game of extracting and processing data. In this sense, the systems that use heterodyne holography may be the harbingers of things to come, because in these the entire system is designed around a method of extracting data. The heterodyne systems do have limitations and require intensive capital investment. I would say, therefore, that considerable openings exist for breakthroughs in holographic and speckle systems that are integrated with data readout and processing.

In the final run, however, the main obstacle to a holographic or speckle metrology industry may be purely intellectual. So long as the search continues for a simple way of getting strain out of holograms and specklegrams, people will ignore the actual complexities of how strain manifests itself in fringe data. They will continue to make the object under test conform to the limits of simple methodology by studying flat disks, cantilever plates, and the like. It does not seem likely to me that a simple solution to the data processing problem exists, but here I should return to my disclaimer. What has amazed and delighted me most about the fields of hologram interferometry and speckle metrology is their capacity for unexpected new developments.