LASER APPLICATIONS

Edited by

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MONTE ROSS

VOLUME 4

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nology undoubtedly has a bright future, not only in the home entertainment field, but also in the area of digital data storage.

The third and last article in this volume describes the technology and engineering problems associated with high-speed laser printing systems. The author, Gary Starkweather, played a central role in the development of the Xerox 9700 copier, which is one of three such systems available today from different manufacturers. Of the various applications described in this volume, high-speed laser printing has achieved the greatest commercial success at this time. A major reason for this success must surely be the relative ease with which light beams can be directed and redirected to particular positions in space.

The Editors hope that this collection of articles will prove helpful to practicing optical engineers who regard the laser as an important tool for the solution of a wide variety of practical problems. Technical progress depends heavily on experience, and we trust that this opportunity to share the experience of others will benefit the reader in his or her future applications of laser technology.

Monte Ross wishes to acknowledge the diligence of his co-editor, Joseph W. Goodman, whose perseverance has resulted in the fine set of articles, which constitute Volume 4.

PREFACE

In this fourth volume of *Laser Applications*, three topics are covered, each representing an application of lasers that has reached a high state of refinement. The articles appearing in this volume are written by individuals who have played important roles in these developments, and who speak from first-hand knowledge of the engineering problems encountered in bringing a new technology to the point of useful application.

In the first article, Robert K. Erf describes the applications of laser speckle to problems of measurement. Since their first observation in the early 1960s, the random interference patterns known as speckle have generally been regarded as nuisances. Speckle reduces the effective resolution of coherent imaging systems, whether these systems use optical, acoustical, or microwave radiation. However, speckle has its redeeming features. In particular, as described in this article, it has been usefully applied to a considerable variety of engineering measurement problems.

The second subject discussed is optical video discs, for which the laser plays an important role in both the recording of master discs and the reading of information from mass-produced copies. The author, A. Korpel, served as Director of Research in Technical Physics at Zenith Corporation during a time period when that company was heavily involved in research on video discs. The development of video-disc technology has been a truly international enterprise, with major efforts in the Netherlands, France, Japan, and the United States. The first commercial optical video-disc players for home entertainment were introduced on a limited basis in December of 1978 through a joint effort of Magnavox and Philips corporations, and further penetration of the commercial marketplace is taking place slowly but surely. This tech-

CONTENTS OF PREVIOUS VOLUMES

CONTENTS

High-Speed Laser Printing Systems

GARY K. STARKWEATHER

APPLICATION OF LASER SPECKLE TO MEASUREMENT

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LASER APPLICATIONS, VOLUME 4

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I. Introduction

In an earlier work (Erf, 1974) the present author introduced the subject of holographic nondestructive testing by suggesting that perhaps it emerged just in time to "save" holography, for at last there was a real application for this visual fantasia. In a later book (Erf, 1978), a brief citation from Stetson's (1975) excellent speckle review paper carried this air of facetiousness several steps further by questioning whether the most practical contribution of holography was to call our attention to laser speckle, for indeed, this phenomenon was most annoying to the serious holographers. Such frivolity is intended simply to indicate that, indeed, it was the intensive study of speckle reduction, a subject undertaken to improve the holographic process and reviewed in detail by McKechnie (1975) in Dainty's (1975) book on "Laser Speckle" that "ignited" the development of speckle metrology.

It should be noted at the outset that the intent of the present article is to review this new technology for performing high-sensitivity measurement from a practical orientation. To this end, experimental methods and applications of speckle metrology will be introduced and described with sufficient illustrative examples to demonstrate its potential. For additional information and more mathematical detail, the previously referenced, edited works "Speckle Metrology" (Erf, 1978) and "Laser Speckle and Related Phenomena" (Dainty, 1975), along with Vest's authored work entitled "Holographic Interferometry" (Vest, 1979), are recommended to the reader. The first, to which considerable reference will be made, along with entries to the original publications, by definition is oriented toward measurement techniques, while the latter two contain contributions on speckle interferometry.

To properly set the stage for discussing the experimental methodology of speckle measurement, the physical properties of speckle are briefly considered in Section II, along with references to detailed accounts of speckle statistics and speckle correlation. With proper mathematical formulation and accompanying verbal description, a precise definition of speckle is possible. However, a visual expression of the phenomenon is far more graphic than words and equations. To this end, Karl Stetson's speckle photographic creation, entitled "Fringe Nebula," is presented as Fig. 1. Artistically fashioned therein is a background of speckle, illustrating the characteristic pattern familiar to anyone who has observed a laser-illuminated scene, overlaid in one area with a "Young's fringe pattern," typical of those obtained during

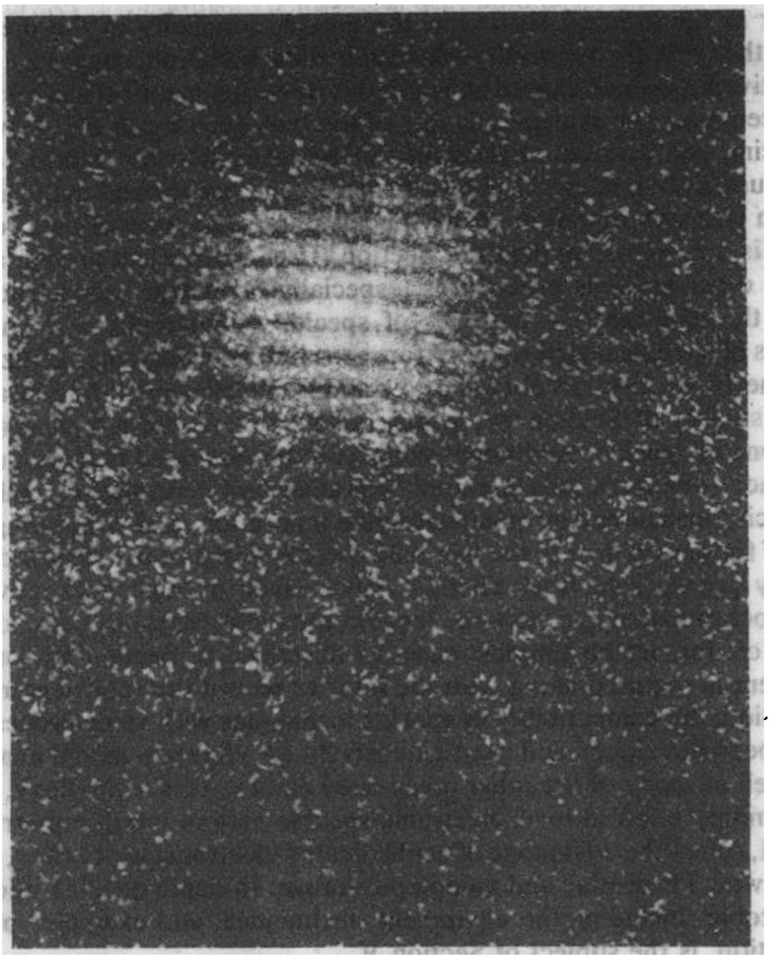

FIG. 1. Karl Stetson's speckle artistry entitled "Fringe Nebula" showing a Young's fringe pattern on a background of speckle.

analysis of a laser specklegram. This particular technique of fringe formation in a diffraction halo is one of the most widely used methods of reducing data from double-exposure laser recordings.

It is perhaps appropriate to note at this point that the fringe characteristics, such as sharpness and contrast, seen in Fig. 1 and depicted throughout the chapter, may not seem as aesthetically pleasing as those obtained by holographic interferometry. (This is especially apparent in the television implementation of speckle metrology to be described later in the article.) However, the greater simplicity of the method, together with the versatility afforded in data reduction, suggests a competitiveness which cannot be ignored in developing optical metrological procedures. For example, fringes of the type depicted in Fig. 1, whose spacing and angular orientation can be quantitatively related to the amount and direction of object displacement, are formed quite simply upon laser interrogation of the specklegram. This form of data reduction is considered in depth in Section III of the present article, along with other analysis procedures (especially full-image reconstruction) and the experimental methods of speckle photography and various types of speckle interferometry for recording specklegrams. Utilization of the fringe data so obtained to measure displacement and strain is one subject of Section IV, which covers several metrological applications of speckle. Additional subjects to be discussed therein include surface roughness measurement, vibration and deformation analysis, velocity measurement, nondestructive inspection, and contouring.

Of further interest is the fact that speckle is one of the easiest of the many popularized laser characteristics (such as high peak powers, monochromaticity, coherence length, and collimation) to take advantage of; for, in the simplest case, as described in Section III, only a camera is required along with the laser to record the specklegram. In addition, the compatibility of speckle techniques with video processing has been developed and used extensively for vibration modal analysis as well as many of the other areas cited earlier. This technology, now commonly referred to as electronic speckle pattern interferometry, or ESPI, offers the advantage of sophisticated electronic processing, coupled with TV display and videotape storage. In-depth consideration of this topic, including the equipment, techniques, and examples of application, is the subject of Section V.

The plethora of possibilities, both in application and execution, indicated here seems to suggest a panacea for problems encountered in optical metrology. It is not surprising, therefore, that speckle, like most technological tools, both old and new, does have its limitations and these are pointed out in Section VI, along with some general considerations relevant to speckle implementation, and comparisons among the various speckle techniques and with holographic interferometry.

As a further introduction to the present chapter, a brief, generalized discussion of speckle terminology is warranted, for as the reader will learn upon delving into the referenced material, there is an abundance of definitions for similar processes. This, of course, is not uncommon in emerging technologies, and the purpose of the following is simply to alert the reader to potential dualities of meaning. Albeit, there is a wide variety of experimental arrangements, as we shall learn in Section III, all of the metrological applications of speckle can be categorized as either speckle photography or speckle interferometry. As an example of the proliferation of terms, the former is often referred to as direct laser photography, and some prefer to think of some versions of the latter as in-line, or on-axis, image plane holography, for the similarity of the setups is clear. Further, some experimenters think of all the techniques as speckle interferometry, and indeed, the verbal distinction is quite subtle. Consider, for instance, that both speckle photography and speckle interferometry involve photography (or other appropriate means of visualization) and, since speckle itself is the result of a self-interference between the coherent wavelets reflected from an optically "rough" surface, both obviously involve interferometry. In addition, utilization of either method generally involves examination of the result in such a way as to yield fringes indicative of object motion. However, in a practical sense, it is the arrangement of the experimental components themselves which generally best defines the process. More importantly, the selection of a method, by whatever name, appropriate to a specific task is the prime consideration, and that is the intent of the following sections.

II. Speckle Properties

Although the phenomenon of speckle is most often associated with the "twinkling" appearance of an object illuminated with a laser, the history of speckle, or speckle-like phenomenon, predates the invention of the laser in the early 1960s by well over 100 years. Not surprisingly, such great names as Newton and Lord Rayleigh, along with others, have been associated with the phenomenon of speckle as related by Dainty (1975) and Goodman (1975). However, the intended purpose of the present discussion is to deal with modern-day applications of the speckle process, with the emphasis on actual engineering measurement problems. In that context, our interest is in the granular appearance; a random distribution of light and dark speckles as seen in the background of Fig. 1, that diffusely reflecting and transmitting surfaces "take-on" when viewed or photographed under laser illumination. This "optical noise" can be quite bothersome because of its deleterious effect on image quality. However, the light contributing to the formation of each individual speckle is fully coherent,[1] and thus speckle is, in effect, a self-interference phenomenon between waves coming from different elementary areas of a rough surface. In our sense, rough refers to random height variations on the order of a wavelength of the light being used and greater. Thus, all but the quite highly polished optical surfaces are candidates for the speckle metrological studies to be discussed herein. Indeed, the phenomenon has been successfully applied to the measurement of surface roughness itself.

A complete treatise on the properties of speckle would include consideration of the statistics of laser speckle patterns and discussions of speckle correlation and related topics. Since the specific details of these subjects are generally not necessary for an experimental understanding of speckle applications to measurement problems, they are felt to be somewhat outside the intended scope of the present coverage, and the reader is referred elsewhere for detailed treatments. Although the possible sources are numerous, Goodman (1975) and Burch (1970) have both dealt extensively with speckle statistics and other topics, while several contributors to "Speckle Metrology" including Stetson (1978a) and Asakura (1978), have given consideration to correlation, and just as important, decorrelation of speckle patterns as it limits application of the methods.

One metrological field somewhat closely tied to the statistics, contrast, and correlation of speckle patterns is that of surface roughness measurement alluded to just earlier. A comprehensive review article on this subject, including the necessary mathematical treatment along with extensive referencing, has been prepared by Asakura (1978). Only a summary of the capabilities of speckle in this area will be provided in Section IV on applications.

However, before proceeding to the speckle techniques themselves, and thence the applications, there is one important property deserving of comment in this abbreviated presentation: speckle size, a statistical

[1] Although not reported in the literature of that day, Ennos had verified the coherent nature of laser speckle in a 1966 experiment (Ennos, 1975) using an optical arrangement not unlike the reference wave speckle interferometers of today. Laser speckles have a measurable intensity and definite phases which are different from, and relatable to, each other. Thus, a few years later, in 1969 [later published (Leendertz, 1970a)], Leendertz reported on the ability to interfere two speckle fields themselves producing a third speckle pattern whose characteristics were dependent upon the relative phase of the original fields.

average of the distance between adjacent regions of maximum and minimum brightness. The importance of speckle size to the user-oriented applications engineer lies in its direct relationship to the geometry and dimensions of the experimental optical system parameters, and its role in establishing limitations on the speckle measurement range. For example, the measurement of in-plane translation can be effected by a double-exposure (one before and one after the object movement) recording of a laser-illuminated object. However, the technique requires the complete separation of the corresponding speckles within the two recorded speckle patterns; thus, the individual speckle size sets the lower measurable limit in such a study.

The speckle size d_{sp} is inversely proportional to the limiting aperture in the optical system and, in terms of the experimental system parameters employed, can be expressed as shown in Fig. 2. In the objective speckle case of Fig. 2a, the size of the limiting aperture is established by the diameter of the laser illumination beam itself. Certainly of more practical interest are those cases involving optical imaging of the diffuse object surface, or subjective speckle, using a lens of focal length f and diameter d_ℓ as illustrated in Figs. 2b and 2c. The latter represents the

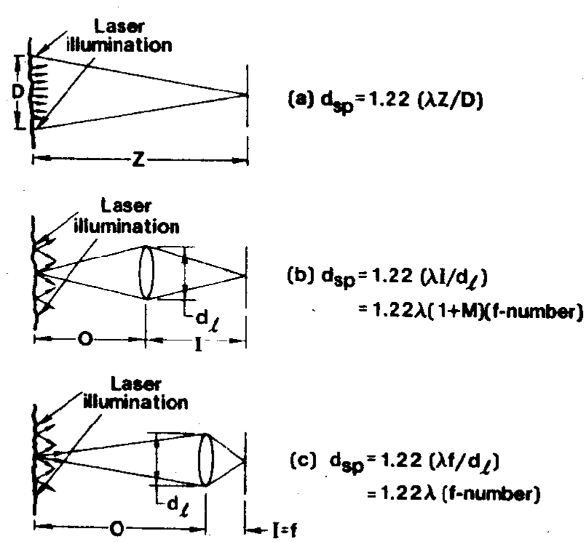

FIG. 2. Parameters and formulation to determine speckle size for: (a) objective case; (b) general subjective case; and (c) subjective case with object at infinity.

limiting case of an object at infinity, or a large distance from the lens ($O \gg\gg f$). In these cases, the diameter of the lens, or the f-number in the limiting case, is the controlling factor. It is also convenient to think of the more general case (Fig. 2b) in terms of the f-number and magnification M of the optical system. Using the standard lens formulation, the image distance I is equivalent to the lens focal length f multiplied by $(1 + M)$. Then, substitution of the f-number for f/d_ℓ provides the second expression shown in Fig. 2b. A similiar substitution (f-number $= f/d_\ell$) also provides the second expression of Fig. 2c. Using the direct proportionality to the f-number, as in Fig. 2c, typical speckle sizes for He–Ne laser illumination can be seen to vary from 1 to 12 μm as the lens is stopped down from $f/1.4$ to $f/16$. A convenient working aperture is $f/4$, inferring a speckle size of ~3 μm for this case, or ~6 μm for the case of one-to-one imaging, i.e., a magnification $M = 1$.

III. Experimental Methods

We have noted the size properties of speckle relative to metrological applications and now turn our attention to the experimental procedures themselves. We shall cover the basic techniques of speckle photography and interferometry in their various forms, along with the data reduction procedures associated with each. Individual discussions of speckle-shearing interferometry and white light speckle will then be presented, and throughout the chapter, appropriate specific examples will be included to illustrate typical areas of application. General comments on lasers, film, stability requirements, and other topics common to the different speckle recording techniques will be deferred to the concluding section of the article.

A. Speckle Photography

Perhaps in its simplest form speckle photography involves the straightforward double-exposure recording of a laser-illuminated object in two different positions or states of stress. Probing of the processed film recording (transparency) with an unexpanded laser beam produces a set of fringes, whose spacing is inversely proportional to the in-plane surface displacement, and whose angular orientation is perpendicular to the direction of displacement. The fringes, "embedded" in a dif-