Speckle Metrology

Edited by

ROBERT K. ERF

QUANTUM ELECTRONICS

Principles and Applications

SPECKLE METROLOGY

QUANTUM ELECTRONICS — PRINCIPLES AND APPLICATIONS

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PREFACE

Had Benjamin Franklin been exposed to the phenomenon of laser speckle, and its ensuing growth as a topic of research to eventual application as a metrological tool, he might possibly have called upon Poor Richard to sententiously document its history thusly:

> Eliminate that which is bothersome,
> And your work shall be the better for it; but—
> Find a use for that which offends thee,
> And thou shalt be twice rewarded.

Indeed, laser speckle, that granular, often annoying pattern produced upon laser illumination of a diffusely reflecting object, came into prominence as the holographer's adversary. While continuing to some degree in that role, although several clever proposals and advances have mitigated its degrading influence, it has been recognized that straightforward speckle photography, quite frequently in double exposure, is extremely useful in its own right. Furthermore, of all the many popularized laser characteristics, such as extremely large peak powers, a high degree of monochromaticity, long coherence lengths, and excellent collimation, laser speckle is perhaps the easiest to exploit because in the simplest case only a camera is required together with the laser. Data reduction techniques for the resultant processed specklegrams, or alternatively, direct photoelectric measurement of the speckle characteristics, have been successfully developed and applied to the measurement of displacement and strain, vibration and deformation, and surface roughness to name just three major categories. And interestingly enough, a most convenient form of data reduction for speckle photographs is based upon Thomas Young's demonstration in the early 1800s (just a score of years after Franklin might have set down his fitting maxim) of the interference of light emerging from a dual pinhole arrangement. Thus, in the late 1960s, using Young's work of over 150 years earlier in confirming the wave theory of light, a new field of measurement, *speckle metrology,* evolved, which has been properly nurtured and sufficiently developed to the point where the present volume was felt appropriate. The intent, of course, is to gather together in one volume representative examples of the extremely diverse array of metrological speckle techniques and applications that have been successfully developed and duly reported, albeit in widely scattered journals and institutional documents.

The book considers both the theoretical concepts and the experimental methods for performing speckle-based measurements, and thus serves the research and development community as well as the practicing engineer in industry. In this way, it is hoped to provide stimuli to the former in the generation of new techniques and applications and further refinement of existing methods, while offering the latter the necessary background and tools to incorporate speckle measurement systems into their instrumentation, inspection, and quality assurance departments. Consequently, considerable detail is provided in describing the methodology, system geometries, data reduction procedures, and specific applications. Following two short chapters that introduce speckle terminology, more fully outline the book's contents, and briefly describe the physical characteristics of speckle, the three major areas of application enumerated above are presented in individual chapters. Then comes one chapter devoted to a discussion of the adaptation of speckle measurement techniques to video recording and processing technology, followed by three chapters on various specific applications of speckle, including its utility in the area of structures inspection. Finally, there is a chapter, intended to serve both the designer and potential user, on the speckle interferometer since this instrument is one of the most widely used for metrological speckle applications.

The editor wishes to acknowledge and thank all the contributing authors from throughout the world, along with those who provided additional illustrative material, for making this book possible. Thanks is also due to several members of the United Technologies Research Center staff who aided in various ways throughout the preparation and production periods. I wish especially to acknowledge E. C. Wingfield for his considerable interest in and encouragement of the project from inception to publication. I am also indebted to K. Csaszar and S. Giggey for their continuing help with the tasks of figure preparation and typing.

CHAPTER 1

INTRODUCTION

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Once the very nemesis of the holographer, speckle has now been profitably exploited and developed into a new optical metrological tool in its own right. Indeed, in 1973 *Applied Optics* recognized the burgeoning activity in the field by including "Speckle Patterns" as a topic heading in its annual index, albeit two of the three entries were concerned with techniques for reducing speckle in holographic experiments. In the following year, 1974, an identical topic heading was introduced in the annual index of the *Journal of the Optical Society of America,* and within two years the number of entries was over 75. It should be noted, however, that the discovery and early practical applications of speckle metrology occurred in England, followed closely by developments in other European countries. Consequently, the first important papers in the field appeared in well-read foreign publications such as *Journal of Physics E: Scientific Instruments, Optica Acta, Optik, Optical Communications,* and *Optics and Laser Technology.* This will become apparent as the reader studies the various reference lists throughout the book.

Further, the universality of the work in this emerging technology continues, with scientists and engineers from countries throughout the world devoting their energies and resources to its development. An examination of the contributors' list to the present volume, as well as the illustrative material, aptly points this out, for it includes writers and/or examples of work from Belgium, Germany, Great Britain, Japan, Norway, Sweden, Switzerland, the United States, and Venezuela. Just as significantly, workers from almost any single one of the aforementioned countries could have provided the bulk of the material contained herein. Thus, it was by design that a multiplicity of nationalities is represented to provide a diverse array of viewpoints on the subject.

Although the phenomenon of speckle is most often associated with the "twinkling" appearance of objects illuminated with a laser, the history of speckle, or specklelike phenomena, 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 have been associated with the

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phenomenon of speckle [1.1]. However, the intended purpose of this multiauthored work is to deal with modern-day applications of the speckle process, with an emphasis on actual engineering measurement problems, together with extensive reference lists for obtaining further information. This is but one of the several current interests in speckle patterns that have evolved since the advent of lasers, which include such diverse topics as information processing and stellar interferometry as well as the ongoing efforts with regard to speckle reduction.

Certainly, it was the last-noted item, reducing the troublesome effects of laser speckle in holography, that spurred the quite intense study of speckle and eventually brought it to the stage of practical utilization that it enjoys today. Further, it was perhaps with this same consideration in mind that Stetson, in a review paper [1.2], facetiously questioned: ". . . how many scholars would be willing to say that the most practical thing holography has done is to have called our attention to laser speckle?" I would think none, for there are a myriad of engineering measurement tasks amenable to various optical methods, of which speckle and holography are but two, and even between these a choice must be made dependent upon the parameters of the problem. Thus, it would seem, as Stetson noted later in his paper, that both will play important roles in the future of optical metrology, most especially because of their ability to provide full surface coverage of test components. There are, however, advantages and disadvantages to both, and throughout the present volume comparisons and trade-offs between the two will be pointed out where appropriate.

Speckle metrology spans a rather wide variety of techniques, all of which generally fall into one of two categories: direct laser (speckle) photography and speckle interferometry. The distinction between the two is somewhat subtle, since both involve photography (or some alternate appropriate means of visualization), and both involve interference. That is, speckle photography certainly depends on the optical properties of speckle, which is itself the result of interference, and, further, utilization of either method (speckle photography or speckle interferometry) generally involves examination of the result in such a way as to yield fringes indicative of the object motion. Thus, in actuality, it may be said that there are no great differences between the two. In practice, there are differences, and these were nicely categorized by Stetson in 1975 [1.2]. He suggested that if there are regions in the two images where the speckle patterns of each are well correlated, let the process be referred to as speckle photography. If, instead, the fringes form as a result of fluctuations in the correlation of the speckle patterns between two images, whether or not there is translation between the correlated portions of the patterns, let the process be called speckle interferometry. There are, of course, differences in the experimental arrangement of the components and additional ways of defining these two general speckle processes. Indeed, many prefer to think of speckle interferometry as in-line, or on-axis, image plane holography, for the similarity of the setups is clear. More importantly, however, both methods have been experimentally adapted to metrological problems in a large variety of ways that are described and illustrated throughout the book.

As a further introduction to the present text, Chapter 2 reviews some basic properties of speckle, and Chapter 3 presents a brief consideration of speckle statistics, together with a detailed discussion of its application to the problem of surface roughness measurement. In addition, some background material relative to the development of speckle technology is included in Chapter 6, in conjunction with that chapter's prime topic of electronic speckle pattern interferometry (ESPI).

Perhaps the greatest interest in this new metrological tool lies in its ability to detect and measure surface movement. Chapters 4 and 5 set down the basic approaches to the measurement of displacement and strain, and vibration and deformation, respectively. The following chapter then illustrates the compatibility of these speckle techniques with video systems, a development which further indicates the attractiveness of speckle for practical engineering applications in industry. This area of study, referred to as electronic speckle pattern interferometry (or ESPI, as indicated above), offers the obvious advantages of TV display and video tape storage, coupled with the potential capability for sophisticated electronic processing in conjunction with computers.

Further utility and adaptation of the various basic experimental speckle techniques to the study of trajectories (Chapter 7) and to topology and structures inspection applications (Chapter 8) are then described. It is especially with regard to the latter, where some large structures are considered, that the compatibility of pulsed lasers with speckle work becomes apparent. This brief note is included here in order to emphasize this versatile aspect of the technology, since the tendency toward continuous wave (cw) lasers in discussing methodology might lead one to believe that pulsed lasers, as well as large objects, are inappropriate sources, and subjects, for speckle application. Further discussion (Chapter 9) of several specialized and unique specific applications of the speckle process to metrological problems includes a few examples that reemphasize the point that pulsed lasers are amenable to speckle photography and interferometry. Contained therein (Chapter 9) are discussions and illustrative examples of its utility in such areas as crack detection in concrete, white light speckle methods, detection of loose relay contacts,