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Introduction and orientation

This chapter states the goals of the book, traces some reasons for its existence, and describes the best ways to use it. Some of the material that appears here would normally be found in an Author's Preface and would, because of its position of exile outside the main text, suffer the fate of being unread. Given the character of this treatise and its somewhat odd but purposeful organization, it seems best to give this commentary the status of a chapter.

1.1 Objectives

The author perceives that a strong need exists for a book about optical methods of experimental engineering analysis, a book that begins from a firm base in the sciences of physics and modern classical optics, proceeds through careful discussion of relevant theory, and continues through descriptions of laboratory techniques and apparatus that are complete enough to help practicing experimental analysts solve their special measurement problems.

This book on optics, interferometry, and optical methods in engineering measurement is primarily a teaching tool, designed to meet that need. It is not intended to be a research monograph, although it contains many examples drawn from research applications. It is not an encyclopedia of results, nor is it a handbook on optical techniques. It grew from lecture notes prepared during the past 25 years for graduate and undergraduate courses in experimental mechanics. These courses are taken by graduate students and seniors who have a variety of educational and professional experiences in several science and engineering disciplines. The preparation of printed class notes began because of the difficulty of teaching without a single textbook that covers optical methods of measurement from the old-fashioned and still-useful photoelasticity through the newer techniques of moire interferometry and electronic speckle pattern interferometry. Instructional literature about the new methods that is useful and understandable for the typical engineering student or strain analyst is still scarce.

Any major piece of writing is, in the end, colored by compromises between purposes that often conflict. It is also reflective, inevitably, of the author's individual experience. In this case, goals concerning utility, completeness, accuracy, length, and efficiency in the teaching environment have dictated development of a particular pedagogical paradigm. Because the resulting organization might seem strange to persons familiar with more typical presentations, such as handbooks or other textbooks, more needs to be said about the goals, the constraints, and the result.

One intent has been to bring into a single binding as much theory and practical information in optical methods of engineering analysis as would be needed by the typical graduating engineer, the graduate student who might utilize some photomechanics in his research, and the industrial stress and motion analyst.

Another important goal is that of scientific accuracy. Mathematical models of optical phenomena tend to be complex and often not especially useful in general form. On the other hand, some commonly accepted simplified models are neither accurate nor physically meaningful. Further, this book is not intended to be another optics textbook, of which we already have several fine renditions.

The major divisions of the text are intended to be as independently useful as possible. The chapters on holography, for example, might be studied without reference to any other part of the book. The sections on moire methods could stand by themselves, and so on.

In opposition to the goals just outlined was a desire to keep the book short and simple enough to be useful as a text in a 30-class-hour course and to be popular with the applied stress analyst as a quick source of answers to immediate problems. Because the contents of optical methods courses vary greatly depending on institution and professor, there is more here than one can comfortably cover in a single course. The idea is to offer some options while keeping the overall coverage adequate.

1.2 Approach and scope

A conventional approach would probably involve several systematic introductory chapters on optics theory. Some weeks of study of these chapters would be required before finally getting to applications, which are the optical measurement techniques themselves. Laboratory experience with the optical methods would start later yet. The result of this approach is that the term or semester is half over before meaningful laboratory experiments can be performed.

The chosen approach, which meets the goals and solves the laboratory scheduling problem, is to integrate theory as much as possible with the development of the optical methods. The theory and the practical use of the theory in the form of important classes of techniques are offered in a series of parcels. Presented at the beginning are just enough optical concepts and theory to understand basic interferometry and handle the mathematics. The concepts are then utilized, first in learning about some classical two-beam interferometers and subsequently in detailed study of one of the oldest of interferometric methods in engineering: photoelasticity. The student is then in a position to do meaningful experiments on these topics while the increment of theory needed to understand the next technique, geometric moire, is presented. This cycle repeats through the entire text.

This methodology seems to be efficient in teaching theory, technique, and laboratory practice in a limited time. In the author's experience, part of the effectiveness arises from the fact that much transfer of learning and reinforcement is incorporated.

Teaching, say, photoelasticity in this way serves several purposes at once. It emphasizes and illustrates all the important concepts of interferometry. The theory is a simple paradigm for the mathematical development of more complex techniques. Photoelasticity is an important and valuable interferometric technique in engineering analysis. The approach gets the students meaningfully involved in the laboratory early on. They are then in a position to go on to more theory and new methods.

The inclusion of much of the material in Chapter 6 on photoelasticity methods has been problematical because of length limitations and perceived distortion of balance in the book. The rationale is that many of the topics are useful in other areas of applied optical interferometry. Additionally, many conventional courses on experimental mechanics concentrate on photoelastic interferometry. In the end, this chapter represents a compromise that seems satisfactory.

Length limitations have affected the product. The book contains no discussion of continuum mechanics or elasticity; some viscoelasticity concepts are outlined in the chapter on properties of model materials because the concepts are important there. Some omissions reflect the author's own ignorance, but he hopes that most of them represent a willful choice that advances the cause of utility. The lack of at least one chapter on shearography represents the major exclusion. The concept of wavefront shearing is generic in that it is used to enhance other forms of interferometry for specific purposes. A useful but balanced treatment of shearography is left for a second edition, should there be one. Similar comments can be made about the exclusion of grid measurement methods and caustics techniques.

The original plan called for an appendix of scripts for a series of illustrative laboratory experiments. These have not been included for several reasons. A major one is that the book grew too long. Second, quite detailed instructions for most of the processes, such as making holograms, optical spatial filtering, obtaining moire fringes, and reducing fringe data, have been incorporated into the text where appropriate. Reiteration of these details seemed redundant. Finally, many of the procedures will be specific to the equipment indigeneous to a given laboratory; a script that covered all eventualities would have been very long and complex. The instructor or student should be able, with minimum investment of effort, to develop a set of experiments that are based on the instructions in the text but are modified specifically for the apparatus in hand.

In the theory developments, the preferred pattern is to start from basics with the simplest sound treatment of the mathematical and physical foundations of the various methods studied. Physical argument rather than mathematics is sometimes exploited to illustrate and explain. Such an approach is not a valid scientific method, but it serves well in teaching concepts. The danger is that it can lead to oversimplified thinking. This trap has been avoided in most instances by following up the conceptualization with rigorous discussion and theory.

The desire that each major section of the book stand by itself is fulfilled to a reasonable degree. It is possible, for example, to read only the section on moire interferometry and make sense of it. It would be better, though, to read the basic optics and moire material in Chapters 2 and 7 first. Even better would be to include Chapter 10. Some maps of this sort are included later in this chapter.

Finally, some comments about references and bibliography are appropriate. The handling of the references supports the primary purpose, which is education. Utility in teaching has been the only fundamental criterion for inclusion of a reference. Only basic papers and reference books on any one technique or piece of theory are cited in the bibliography. These will lead into the body of research literature on a given topic, should the reader want to pursue it. Exceptions are where controversy is perceived or where the origins of a particular treatment seem clearly connected. When there is a choice, published books are cited in preference to proceedings, theses, and reports. There is no intent to slight or promote any person's work, to assign criticism or credit, or to act as arbiter of turf disputes. This approach to the bibliography requires much judgment on the part of the author. Lapses are inevitable; one hopes that they are not incredible!

Given the broad coverage of the book, the development of a consistent notation that is appropriate for all the methods has been incompletely accomplished. It has not seemed wise to carry such a movement to the extreme. Historically conventional notation for photoelasticity is not entirely compatible with that used for moire interferometry, for example. For this reason, a list of symbols is not included; rather, the meanings are made clear by defining them in the local context.

1.3 Motivations

The last three decades or so have produced many important advances in the discovery and understanding of optical phenomena, in the refinement of optical techniques of measurement, and in the utilization of interferometry to solve problems in physics and engineering. Indeed, many advances in optics theory and technology have been stimulated by the demands of engineering research.

From another viewpoint, one observes that the science of optics unifies and expands diverse important areas of experimental research. Fundamental problems in rapidly developing areas – such as fluid mechanics, rock mechanics, biomechanics, fracture mechanics, materials science, manufacturing technology, nondestructive inspection, and glacier mechanics – are being solved by new methods of optical metrology. Examples of these methods include speckle interferometry, acousto-optic holography, infrared photo-elasticity, holographic interferometry, white-light speckle photography, advanced moire methods, electronic speckle, laser Doppler velocimetry, and optical data processing.

It is a fact that much of the development and many of the applications of advanced optical techniques of experimental mechanics have been carried out by dedicated and capable individuals or small groups in government, university, and industrial laboratories. On the other hand, many of the measurement applications are pursued by people whose backgrounds are in engineering and who have little formal training in optics. The discovery of new phenomena and the invention of new methods tend to be concentrated in physics laboratories, and much of this development of optical techniques is undertaken by specialists who might have a rather narrow concept of applications. Problems-oriented experimental engineering persons tend to be less aware of new choices and conservative in selection of experimental methods.

The need for a book of this type has been perceived by teachers and practitioners in engineering research for many years. It has also been obvious that such a treatise would be very difficult to write, partly because the sheer volume of material is forbidding and partly because of the breadth of background required of the author.

This textbook is a sincere attempt to provide this long-needed bridge, which will tie experimental engineering analysis firmly to its parent sciences while meeting the responsibility of providing training in old and new optical methods of experimental analysis.

1.4 Suggestions for using the book

This text was prepared for both the academic and the industrial laboratory environments, and there are several patterns by which it can be effectively used.

The general sequence to be remembered is that an increment of theory is presented and then a method that utilizes that theory is developed. Thus, the student can perform a laboratory experiment involving that method while learning the next increment of theory.

1.4.1 As a textbook in a graduate course

Consider first the use of the text in a typical graduate course in optical methods, which probably comprises thirty lecture hours and about the same number of laboratory hours. In that case, the first week of instruction deals with Chapters 1 and 2, with only cursory treatment, if at all, of the section on matrix methods. Chapter 3 can be examined to any depth desired, depending on purpose and student interest. If the emphasis is on mechanics-type analysis, Chapter 3 is given only about one-half hour of lecture, which is sufficient to place interferometry in its historical context. At the beginning of the second week, the students are in position to do a meaningful experiment on geometric optics and basic interferometry using Young's fringes, Newton's rings, or basic Michelson interferometry. While this is going on, photoelasticity theory is discussed, with emphasis on the fact that it serves as a paradigm for other interferometric methods while also being very useful in engineering analysis. The class should be well into Chapter 4 at the end of week 2, and they can begin experiments on photoelasticity as Chapter 5 is begun.

At this point, some decisions need to be made about the direction of the course. If skill in photoelasticity is to be attained, then considerable time with the broad range of material in Chapter 6 is necessary. Otherwise, some selected topics from this chapter can be discussed at less-than-thorough depth to round out the overall understanding of the topic and to provide some information that will be useful later in the course. Calibration of materials, model similarity and scaling laws, compensation methods (now called phase measurement techniques in other contexts), and the concepts behind reflection and three-dimensional photoelasticity can be covered, for example.

The next topic is geometric moire, which is discussed while the students are finishing the photoelasticity experiments. Here again, the depth of treatment can be adjusted to the goals of the course. Study of only Chapter 7 is sufficient to aid in understanding the more sophisticated moire techniques. If some skill is to be developed and an experiment on geometric moire is to be conducted, then Chapter 8 and/or Chapter 9 will be useful.

Attention is then turned to the very important topic of diffraction by an aperture. Chapter 10 should not be slighted, no matter what is to follow in the course, because this material is fundamental to much of the subsequent development. Chapter 10 is the second of the twin pillars of the book, the other being Chapter 2. They are separated by many pages and by about a month's study, for good reasons having to do with scheduling the laboratory experiments, developing the requisite mathematical skills, maintaining student interest, and teaching effectively.

From here on, the sequence and depth can be adjusted to suit goals and interests. The material on intermediate sensitivity moire, Chapter 11, builds on geometric moire and is a good practical application of diffraction theory. It is a useful improvement on geometric moire, and it is quite easy to set up a laboratory experiment to illustrate the method.

Alternatively, one can skip to moire interferometry, holographic interferometry, or speckle methods at this point. There is some sequential dependence among these topics, but it has been held to a minimum. If utility in engineering analysis is the major concern, then at least the basics of moire interferometry should be covered. This would comprise most of the first seven sections of Chapter 13 and the two short Chapters 14 and 15. A one-dimensional version of a moire interferometer with minimum adjustments can be set up for the laboratory experiment on this method. An effective alternative is, for this one instance, to rely on a laboratory demonstration with a television camera to show the fringes.

Most students are keen on making holograms and doing simple holographic interferometry, so this topic will probably be an essential part of the course. From the pedagogical viewpoint, discussion of this subject effectively rounds out the understanding of interferometry. The experiments are quite easy to set up. Given typical laboratory budgets, the instructor must be careful to limit film and plate usage, but much practical experience is gained through these experiments.

The final topics in a course with practical orientation are contained in Chapters 18 and 19 on the speckle phenomenon and speckle photography. As with holography, an experiment on speckle photography is easy to set up and effective in terms of teaching and time limitations. Speckle correlation and electronic speckle can be discussed as the closing topics while the students are finishing laboratory experiments. If electronic speckle apparatus is at hand, a demonstration of it is useful because it illustrates an important direction of future development.

1.4.2 As text for a survey course

This material has been used successfully as one of the source books for a senior-level introductory course that covers all the basic methods of strain analysis and motion measurement. It is augmented by materials that cover strain gages and accelerometers. Roughly fifteen class periods are used for discussion of optical techniques. The development of in-depth skill is not a goal. The emphasis is on fundamental concepts and capabilities.

In this type of course, Chapters 1 and 2 are covered but in less depth than before and with emphasis on the concepts of interferometry. Chapter 4 is presented, and either a demonstration of photoelasticity is conducted or else a simple "canned" experiment is performed by the students. Only sections 4–6 and 9 of Chapter 5 are discussed, with emphasis on the procedure rather than the mathematics. The general ideas of stress separation, reflection photoelasticity, and three-dimensional photoelasticity are presented in about two class hours.

The first halves of Chapters 7 and 8 are then discussed. Again, either a demonstration or a simple experiment on geometric moire is offered.

One class hour is then devoted to discussing the concept of diffraction at an aperture and the lens as a Fourier analyzer, with examples.

At this point, the class is in position to cover all or any of the remaining topics at the depth desired for the time left. Coverage of the first nine sections of Chapter 16 on holographic interferometry, with the mathematics de-emphasized in favor of physical concepts, is recommended. This is supported by another demonstration or a basic holography experiment.

The course closes with study of the first halves of Chapters 18 and 19. Demonstrations of speckle photography and, perhaps, electronic speckle provide an effective and forward-looking end.

1.4.3 As a laboratory source book

This book should be useful for the laboratory manager or technician who needs a speedy solution to a certain measurement problem. Review of the strengths and weaknesses of the various methods will indicate which techniques might be most appropriate for a given application. The user can then concentrate on only the section that seems to offer the best probability for solving the problem. One must remember that the technique must be chosen and modified to fit the problem, and that the reverse leads to trouble.

The major divisions of the book are written so that they can stand by themselves to a significant degree. Part V on moire interferometry or Part VI on holographic interferometry, to name two examples, can be studied without reference to other sections, assuming that the reader has some minimal background in optics. Otherwise, preliminary study of Chapters 2 and 10 is advised. A technician who needs to quickly set up a holographic interferometry experiment could even begin with a reading of only Chapter 17 and expect success in the laboratory.

1.5 Closure

The author's fervent wish is that this book will prove useful. Considerable effort has been expended in editing for accuracy, and contemplation of mistakes is distasteful. Given the breadth of coverage, however, it seems inevitable that the work must contain some errors. The author hopes that the mistakes will be neither foolish nor serious. Users of the book are cordially invited to offer constructive comments and corrections, which might lead to an improved second edition.

PART I

Optics and interferometry