Annotated bibliography of optomechanical design

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Abstract. Literature in the field of optomechanical design is reviewed, including selected papers and texts that should provide the optical engineer with information needed in various phases of design. These references are accompanied by short annotations. Beyond citation of general texts in optics, the areas covered include materials, tolerancing and specification, mounting, mechanical and thermal analysis, positioning, stabilization, baffling, assembly and alignment, and scanning.

Subject terms: optomechanical design; bibliography; materials; tolerancing and specification; mounting; mechanical analysis; thermal analysis; positioning; stabilization; assembly and alignment; scanning.

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1. INTRODUCTION

In the process of organizing a seminar course on optomechanical design, I found it difficult to locate many references on the subject. When the course started, I had only an old one-page list compiled by someone in his spare time and a volume of *Optical Engineering* that featured papers on optomechanical design. Since one of the requirements of the course was to review an article in the field each week, while my course ran its course, the students in mechanical engineering and physics dug up additional references. By the end of the quarter I had the beginning of a substantial bibliography on optomechanical design. Starting with these citations, I made several database searches. Although a number of comprehensive databases were searched, the results were modest, despite many permutations of search terms. The most useful resources in compiling this bibliography were reference lists given to me by two colleagues. The best system is to find an expert who knows the field.

Since the field of optomechanical design encompasses so many disciplines, the literature that might be relevant is potentially enormous. There was a need to be selective. I was looking for papers that presented equations, figures, tables, or examples that I would find useful in designing systems or that extended the material available in the general texts in the field. As it was, I found about 600 titles. Of these, I examined about half in more detail and then copied and read about half again, or 150 titles. Some of the papers, although interesting, were too general to be of much use, while others were so detailed that they would have been relevant to only a small segment of the optics community. This paper is an attempt to provide an annotated listing of the literature available on optomechanical design. It follows a format similar to one on lasers that I coauthored for the American Association of Physics Teachers.*

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*D. C. O'Shea and D. C. Peckham, Am. J. Phys. 49, 915 (1981). Also reprinted in *LASERS: Selected Reprints,* D. C. O'Shea and D. C. Peckham, eds., Am. Assoc. of Phys. Teachers, Stony Brook, N.Y. (1982).

It will be noted that a large number of the references are to be found in *Proceedings of SPIE — The International Society for Optical Engineering*. These proceedings are the records of conferences held by that organization and others. The papers published there are unrefereed and, therefore, do not represent the same level of publication as refereed papers published in journals such as *Applied Optics* and *Optical Engineering*. Considering the nature of the optomechanical designer, who is usually in the middle of his or her current alligator-filled swamp, it is good luck if anything gets written down; a proceedings paper may be all that is ever recorded about his or her experiences. We'll take what we can get. However, the assertions in proceedings papers should be read with the proper skepticism of any good scientist or engineer.

Note: This paper is the basis for an SPIE Milestone Series volume on Optomechanical Design to be published in early 1987. The asterisks (*) preceding the citation numbers herein indicate that those papers will be included in the Milestone volume, subject to permission from the copyright holder.

2. TEXTS

Until recently there was no text in the field of optomechanical design. This has been remedied by a new publication:

2.1. *Opto-Mechanical Systems Design,* Yoder, Paul R., Jr. (Marcel Dekker, New York, 1986). A comprehensive review of the field by one of its foremost practitioners. The breadth of coverage, the large number of illustrations, and the extensive list of references make this book the major reference manual in the field of optomechanical design.

Prior to this text, one of the few collections of papers in this field was

2.2. *Optical Engineering,* Vol. 20, No. 2, Yoder, Paul R., Jr., guest editor (March/April 1981). Eleven papers on optomechanical systems design based on revised versions of SPIE conference proceedings papers.

Other texts that contain basic information in the areas of optical design and optical engineering are

2.3. *Fundamentals of Optical Engineering,* Jacobs, Donald H. (McGraw-Hill, New York, 1943). While the material in this book is not recent, the discussions on optical instrument design (Chap. XVII), bearings (Chap. XIX), gears, clutches, coupling (Chap. XX), and lens mountings, parallel displacements (Chap. XXI) are still useful.

2.4. *Modern Optical Engineering,* Smith, Warren J. (McGraw-Hill, New York, 1966). Basic reference in optical engineering. Chapter 7 discusses optical materials and coatings; Sec. 14.3 provides a brief overview of optical mounting techniques.

2.5. *Applied Optics — A Guide to Optical System Design,* Vol. 1, Levi, L. (Wiley, New York, 1968); Vol 2. (Wiley, 1980).

2.6. *Optical Design, MIL - Handbook - 141,* U.S. Department of Defense (U.S. Government Printing Office, Washington, D.C., 1962). Available from the Naval Publications and Forms Center, Tabor Avenue, Philadelphia, PA 19120.

2.7. *Applied Optics and Optical Engineering,* Kingslake, Rudolph, or Shannon, Robert, and Wyant, James, eds. (Academic Press, New York, 1965). This series of monographs covers a wide range of topics in the field of optical engineering. Separate papers relevant to optomechanical design are listed herein under individual authors.

2.8. *Lens Design Fundamentals,* Kingslake, Rudolf (Academic Press, New York, 1978). The first chapter briefly treats the materials, mounting, and tolerances in an optical design.

A somewhat different paper that addresses other concerns of the optical engineer is

***2.9.** "Designing a durable system," Yoder, Paul R., Jr., Mach. Design, p. 190 (May 23, 1968). Nonoptical considerations in the design of optical systems, including protection against abuse, optical defects, radiation protection, estimation of service life, maintenance, and ergonomics. A qualitative, rather than quantitative, discussion of topics.

Finally, in the way of texts, no optical engineer should be without the best current reference on the testing of optics:

2.10. *Optical Shop Testing,* Malacara, Daniel, ed. (Wiley, New York, 1978).

3. MATERIALS

Although many of the texts cited above provide some data on the properties of optical materials, the amount of information they convey on this subject is limited. Some more specialized papers that may aid the optomechanical designer in his or her efforts to understand the range and limits of the materials available for refractive and reflective optics are

3.1. "Optical materials — refractive," Parker, Charles J., Applied Optics and Optical Engineering 7, 47 (1979). Describes the properties of refractive materials, glasses, crystals, and plastics. Includes information on materials for the infrared. The reference list supplies additional sources.

3.2. "Optical materials — reflective," Barnes, William P., Applied Optics and Optical Engineering 7, 97 (1979). Describes the properties of materials used as substrates for reflectors. Contains a useful table of properties of a dozen materials.

As opposed to the reflective optics of the past that were metallized glass substrates, metal optics have come into wide use with the advances in diamond-point turning:

***3.3.** "Selection of materials and processes for metal optics," Paquin, Roger A., in *Design, Manufacture & Application of Metal Optics,* W. P. Barnes, Jr., ed., Proc. SPIE 65, 12–19 (1975). A laundry-list paper that provides a complete listing of the materials used in metal optics and the properties that must be considered (but only a few actual values). This is a good paper if you want to make sure you touched all bases in a metal optic design.

Another field of materials that has had an impact is that of composite materials:

***3.4.** "Graphite/epoxy material characteristics and design techniques for airborne instrument application," Stumm, J. E., Pynchon, G. E., and Krumweide, G.C., in *Airborne Reconnaissance V,* R. J. Bannach, ed., Proc. SPIE 309, 188–198 (1981). Discusses material selection, thermal expansion coefficient matching, moisture suppression, and orientation of graphite/epoxy (G/E) directions in an optical system. Includes comparison of G/Es to other materials. Integration and transitions between materials are explored.

Plastics have also changed the manner in which optical systems are designed. This is particularly true if the system is going to be made in large numbers. The following three references provide information on overall use of plastic optics and specific data on two of the most used plastics:

3.5. "Optical materials — plastic," Welham, Brian, Applied Optics and Optical Engineering 7, 79 (1979). Describes the properties of plastics. Includes information on design and manufacturing of plastic optics.

***3.6.** "Plastic optics for opto-electronics," Pasco, I. K., and Everest, J. H., Optics and Laser Tech. 10, 71 (1978). Listing the most useful types of plastics and some of their properties. Contains descriptions of some designs, but no insights into the design process or calculations.

***3.7.** "Optical and physical parameters of Plexiglass 55 and Lexan," Waxler, R. M., Horowitz, D., and Feldman, A., Appl. Opt. 18, 101 (1979). One of the few places that you can find most of the parameters needed to design with methyl methacrylate (Plexiglass) and polycarbonate (Lexan).

Because many of the parameters of plastics have larger thermal coefficients than glasses, they must be designed with this in mind. In Sec. 7 there are a number of references dealing with athermal design of such systems.

At the other end of the materials spectrum are the high stability metals that can be used to reduce or eliminate sensitivity of optical systems to thermal variations:

3.8. "Dimensional stability of Invars," Jacobs, Stephen F., Shough, Dean, and Connors, Cliff, Appl. Opt. 23, 3500 (1984). For high precision optical systems it is necessary to maintain extremely stable separations between certain components over extended periods of time. The results reported in this paper provide stability data on a number of low expansion steels (Invars).

4. TOLERANCING AND SPECIFICATION

One of the least understood aspects of the field of optomechanical design is that of specifying an optical design. Closely allied to this is the effect that tolerancing a design has on costs. Part of the design of a system includes the dimensioning of the various parts so they fit together properly and, in the case of sliding or rotating parts, choosing the proper materials to eliminate or reduce wear over the lifetime of the system:

***4.1.** "Dimensioning parts so they fit," Spahr, R. H., and Tibbets, E. D., Mach. Design, p. 157 (Sept. 20, 1973). A review of a number of dimensioning strategies that ensure fitting of mating parts without assigning tolerances that are too restrictive or costly. Positional, natural, variable, and profile tolerancing are discussed, along with phantom gaging and datum feature dimensioning.

4.2. "Designing for zero wear," Bayer, R. G., Shalkey, A. T., and Wayson, A. R., Mach. Design, p. 143 (Jan. 9, 1969). An engineering model is described that predicts conditions for "zero wear," wear that does not exceed the surface finish of the contact surfaces. A large number of geometries and materials-lubrication conditions are considered.

4.3. "Designing for measurable wear," Bayer, R. G., and Wayson, A. R., Mach. Design, p. 118 (Aug. 7, 1969). Extension of material discussed in "Designing for zero wear."

One of the contributions of SPIE's series of proceedings is the rapid distribution of information in fast-moving fields. Two conferences on specifications have been organized:

4.4. *Contemporary Optical Systems and Component Specifications,* Fischer, Robert E., ed., Proc. SPIE 181 (1979). This proceedings encompasses four sessions: System Specification and Tolerances, Optical Component Specification, Specification of Scattering, Materials, and Coatings, and Optical Standards. Particularly interesting is the panel discussion at the end of the volume.

4.5. *Optical Specifications: Components and Systems,* Smith, Warren J., and Fischer, Robert E., eds., Proc. SPIE 406 (1983). This proceedings consists of 14 invited papers on optical specifications and a panel discussion. Although most of the papers address specifications, some review the standards used to specify certain optical parameters.

Individual papers from these proceedings are cited herein.

Trying to gain a handle on the effects of tolerancing on costs has occupied a number of fabricators. The following papers represent their attempts:

***4.6.** "Optical component specifications," Parks, Robert E., in *1980 International Lens Design Conference,* R. E. Fischer, ed., Proc. SPIE 237, 455–463 (1980). "Three areas of optical component specification are discussed . . . : (1) purely optical, (2) opto-mechanical, and (3) . . . scattering specifications. Emphasis is placed on the level of tolerancing as it affects the function of the final optical system. Numerous graphs and tables . . . ." (from abstract).

***4.7.** "Trends and limits in the production of optical elements and optical systems," Kuttner, Paul, in *International Seminar on Advances in Optical Production Technology,* Proc. SPIE 163, 24–30 (1979). Lists tolerances achievable today, estimates of attainable future tolerances, and methods of testing for such tolerances. A series of tables is given on tolerances for glasses, lens fabrication, barrel fabrication, individual element mounting, and entire optical systems.

***4.8.** "Tolerancing for economies in mass production of optics," Plummer, John L., in *Contemporary Optical Systems & Component Specifications,* R. E. Fischer, ed., Proc. SPIE 181, 90–92 (1979). A short review of tolerancing optics by a fabricator of optics. Contains a number of guidelines for individual tolerances and cost multipliers for imposing tighter tolerances.

***4.9.** "The impact of tight tolerances and other factors on the cost of optical components," Willey, Ronald R., in *Optical Systems Engineering IV,* P. R. Yoder, Jr., ed., Proc. SPIE 518, 106–111 (1985). Within this description of an optical fabrication estimation system are included a number of estimation algorithms that show agreement among independent observers. These algorithms can serve as a starting point for those doing their own estimations. The paper includes additional references.

***4.10.** "Techniques for characterizing optical system fabrication," Thompson, Kevin P., in *Optical Alignment II,* M. C. Ruda, ed., Proc. SPIE 483, 16–23 (1984). The rationale and approaches for describing the optical errors in a series of optical elements and spaces are presented. Although intended for use in sensitivity analysis, equations are not given. However, a description is given of how the parameters are measured after fabrication.

Documentation of specifications and tolerances is something that excites very few people in the field, but it is absolutely necessary for reliable and efficient production. The two papers listed here describe how some divisions of Hughes Aircraft Company and the Perkin-Elmer Corporation, respectively, carry out this task.

***4.11.** "Outline of tolerancing (from performance specification to toleranced drawings)," Ginsberg, Robert H., Opt. Eng. 20(2), 175–180 (1981). The documents and methods needed to establish a procedure for tolerancing an optical system are described. Includes flowchart of procedures and examples of a sensitivity table, an error budget, an optical schematic, and an optomechanical layout.

***4.12.** "Specifying the optical system with an optical design data sheet," Yoder, Paul R., Jr., and Casas, R. E., in *1980 International Lens Design Conference,* R. E. Fischer, ed., Proc. SPIE 237, 516–523 (1980). The specification system used at Perkin-Elmer is described. Consisting of five or more sheets of specifications and tolerances, the system is flexible and extendible to any number of surfaces. A completely filled out example is given.

An example of tolerancing is

***4.13.** "Influence of specification on tolerancing of high-volume optics," Koval, Edward J., in *Contemporary Optical Systems & Component Specifications,* R. E. Fischer, ed., Proc. SPIE 181, 30–32 (1979). A short, effective demonstration of tolerancing using a single plastic camera lens as an example. The example is neither trivial nor unwieldy.

Two special kinds of specifications are those for optical systems that include the human eye as a detector and those for systems incorporating plastic in the design:

***4.14.** "Specifying the visual optical system," Walker, B. H., in *Contemporary Optical Systems & Component Specifications,* R. E. Fischer, ed., Proc. SPIE 181, 48–54 (1979). "This paper presents a cursory discussion of the visual optical system . . . . A typical visual system will be discussed in detail, illustrating the required breakdown of its specification into two major areas, basic optical characteristics and system image quality" (from abstract).

***4.15.** "Specifying glass and plastic optics — what's the difference?" Lytle, John D., in *Contemporary Optical Systems & Component Specifications,* R. E. Fischer, ed., Proc. SPIE 181, 93–102 (1979). Describes the freedom offered and the constraints imposed by using plastic optics in a design. The tolerancing of plastic optics differs radically from glass optics because of the uniformity of molding.

5. MOUNTING

Once an optical design is finished, there remains the problem of holding the elements in the correct locations with respect to one another. The mounting of lenses, mirrors, and other optical components poses a challenge to the most skilled of designers. While there are certain broad principles, almost every design has its exceptions.

The first three papers give simple illustrations of mounting optical components:

***5.1.** "Aerospace mounts for down-to-earth optics," Richey, Charles A., Mach. Design, p. 121 (Dec. 12, 1974). A rapid tour of many types of optical mounts, graphically presented with little or no discussion or calculation. Still, the paper represents a wide range of mounting ideas, including some simple ones you may not find anywhere else.

***5.2.** "Stability of optical mounts," Durie, D. S. L., Mach. Design, p. 184 (May 23, 1968). Brief overview of the mechanical properties of glass and mounting of mirrors, prisms, and lenses. Some simple examples are given, but no extensive calculations are done. Short discussions of thermal stabilization and vibration minimization.

***5.3.** "Mounting optical elements," Cade, J. Weldon, Mach. Design, p. 133 (July 8, 1965). A three-page pictorial summary of techniques for mounting small optical components (lenses, mirrors, and prisms). Compared to other papers, a highly oversimplified look at mounting.

5.A. Lenses

The next series of papers provides substantially more quantitative guidance in lens mounting. The first paper, by Bayar, is a particularly useful introduction to the basics of the field:

***5.4.** "Lens barrel optomechanical design principles," Bayar, Mete, Opt. Eng. 20(2), 181–186 (1981). Selection of materials for lens barrels, techniques for constraining a lens radially and axially (including simple equations for calculating stresses on components), and short discussions on cementing and sealing lens assemblies. Earlier version in *Optical Systems Engineering,* P. R. Yoder, Jr., ed., Proc. SPIE 193, 92–100 (1979).

***5.5.** "Lens mounting techniques," Yoder, Paul R., Jr., in *Optical Systems Engineering III,* W. H. Taylor, ed., Proc. SPIE 389, 2–11 (1983). Review of a number of mounting techniques with numerous examples. Equations are given for stress created by various mounting geometries. Lathe assembly of optical elements in their mounts is described.

5.6. "Lens mounting and centering," Hopkins, R. E., Applied Optics and Optical Engineering 8, 31 (1980). After discussing the basic principles of lens mounting, the author describes the components of a lens mount and the techniques and tests used in centering a lens. A section on tolerancing a lens and its mount and an example round out the paper.

***5.7.** "Étude bibliographique des méthodes de centrage des lentilles a surfaces sphérique," Jaunet, G., and Marioge, J. P., Nouv. Rev. Optique 6, 353 (1975). A descriptive review of a number of mechanical, optical, and interferometric methods for centering lenses. The automation of some of these methods is discussed. (In French.)

***5.8.** "Mounting of lens elements," Delgado, Raymond F., and Hallinan, Mark, Opt. Eng. 14(1), S-11 to S-12 (1975). A short paper giving equations for estimating the compressive and tensile stress due to the mounting of lens against a spacer in both sharp-edge and tangent geometries. An equation for spacer thickness also is given.

One source not available through the standard journal literature or proceedings can be obtained through the National Technical Information Service (NTIS):

5.9. *A User's Guide to Designing and Mounting Lenses and Mirrors,* Kowalskie, Bryan J. (Lawrence Livermore Laboratory, Livermore, CA, 1978). "This guidebook is a practitioner-oriented supplement to standard texts in optics and mechanical engineering . . . intended as a primer for engineers, designers, and draftsmen already familiar with some of the problems encountered in mounting optical components . . . " (from abstract).

Information on the costs of microfiche and paper copies of the above reference can be obtained by writing NTIS, U.S. Dept. of Commerce, 5285 Port Royal Road, Springfield, VA 22161. The document number, UCRL-52411, should be included in your request for information.

Once the basics of lens mounting are mastered, the procedure can be improved by using precision methods for centering the elements and their receiving barrels. Both mechanical and interferometric centering techniques are described in these papers:

***5.10.** "Some thoughts on lens mounting," Hopkins, Robert E., Opt. Eng. 15(5), 428–430 (1976). Discussion of alternative methods to centering lenses by shifting precision centering requirements from grinding edges in an optical shop to precision machining and precision assembly using collimated laser light.

***5.11.** "High performance lens mounting," Jones, G. E., in *Quality Assurance in Optical and Electro-Optical Engineering,* L. R. Baker, ed., Proc. SPIE 73, 9–17 (1975). A description of cell-based lens mounting and assembly is given, and three examples of such designs are illustrated. No numbers are presented, but an analysis of the advantages and disadvantages of the procedures is given.

***5.12.** "Procédés de centrage des surfaces optiques," Jaunet, G., Marioge, J. P., et al., J. Optics (Paris) 9, 31 (1977). "This article describes two high accuracy lens centering devices adapted to various [techniques] of centration. One of them can be used in an automatic system" (from abstract). (In French.)

***5.13.** "Design and fabrication of high performance relay lenses," Westort, Kenneth K., in *Optical Systems Engineering IV,* P. R. Yoder, Jr., ed., Proc. SPIE 518, 40–47 (1985). A comprehensive discussion of the tolerances in edge-mounting two- and three-element lenses in a lens barrel. Current and future fabrication techniques are explored. An excellent paper.

5.14. "High-precision, strain-free mounting of large lens elements," Deterding, Leo G., Appl. Opt. 1, 403 (1962). A method is given that uses a precision rotary table, a dial indicator, a microscope, and a small reticle. An element's optic axis is located, and the element is mounted using a potting compound in strain-free mounts. The mounts are assembled and soldered in the main lens cell.

***5.15.** "Some experiments on precision lens centring and mounting," Carnell, K. H., et al., Opt. Acta 21, 615 (1974). "Centring was done by interferometric measurement of surface height and the lens cells were assembled in plain diamond turned barrels; improvements in symmetry of about an order of magnitude over results previously reported were found" (from abstract).

Another paper, from the same group as the last reference, describes redesigning a system as the actual values of the assembled parts are measured. This obviously is not intended for large volume optics, but it might prove useful when only a few systems are to be built or a design is being prototyped.

***5.16.** "Precision construction of optical systems," Reavell, F. C., and Welford, W. T., in *Optical Alignment,* R. N. Shagam and W. C. Sweatt, eds., Proc. SPIE 251, 2–4 (1980). A method of mounting a series of lenses is described. The unique feature of this paper is the measurement of component parameters at various points in the process, thereby providing reoptimized designs. Centering, mounting, and choice of materials are also described.

In some situations lenses can be subjected to considerable mechanical shock:

***5.17.** "Maintaining optical integrity in a high-shock environment," Lecuyer, John G., in *Optomechanical Systems Design,* M. Bayar, ed., Proc. SPIE 250, 45–49 (1980). Consideration of the techniques used to ensure performance in systems subjected to shock. Most degradation was found to be due to vibration and not to shock. Effect of optical errors on system performance is discussed, and some solutions are offered.

Vibrational analysis references are listed in Sec. 6 in this paper.

5.B. Mirrors

As optical systems increase in size, there is a tendency to shift the burden of providing optical power from lenses to mirrors. For small optics the same mounting techniques used with lenses would apply to mirrors. But for large mirrors the solutions tend to be more diverse than for lenses.

***5.18.** "Strain-free mounting techniques for metal mirrors," Zimmerman, Jerrold, Opt. Eng. 20(2), 187–189 (1981). Properties of metal mirrors and figures of merit for four metals. List of design principles for strain-free mounting. Five examples are given, but the descriptions are so brief that their usefulness is limited.

5.19. "Optical mirror-mount design and philosophy," Chin, David, Appl. Opt. 3, 895 (1964). Describes a number of mirror-mounting techniques. Certain sections require an understanding of mechanical engineering concepts.

Three examples of mirror mounting are given in the following papers:

5.20. "Improved mirror mounting for optical interferometers," Embleton, T. F. W., J. Opt. Soc. Am. 45, 152 (1955). Description of a mirror mounting in which rotational adjustments of the mirror are made about axes through the center of the surface. Since photographs rather than diagrams were used, the construction is somewhat difficult to discern.

5.21. "Design of Infrared Astronomical Satellite (IRAS) primary mirror mounts," Schreibman, Martin, and Young, Philip, Opt. Eng. 20(2), 190–194 (1981). A comparison between a hard mount design for a metal mirror and a flexure mount. Lists trade-offs between different approaches. Illustrates a cruciform section plus blade section flexure mount.

5.22. "Optical effect of flexure in vertically mounted precision mirrors," Schwesinger, Gerhard, J. Opt. Soc. Am. 44, 417 (1954). An analysis of distortions produced by gravity in vertically mounted mirrors, using analytical rather than finite element analysis techniques.

5.C. Planar optics

The mounting of flat surfaces, mirrors, prisms, and beamsplitters is as important as that of image-forming optics. The first of these references is a good overview on the subject:

***5.23.** "Non-image-forming optical components," Yoder, Paul R., Jr., in *Geometrical Optics,* R. E. Fischer, W. H. Price, and W. J. Smith, eds., Proc. SPIE 531, 206–220 (1985). "In this paper we review the geometrical characteristics of optical components that do not form images themselves... . Representative configurations for these components and typical designs for mounting into common types of instruments are also described" (from abstract).

***5.24.** "Optomechanical considerations for optical beam splitters," Lipshutz, Marvin L., Appl. Opt. 7, 2326 (1968). A short note on mounting beamsplitters. Three examples are illustrated.

5.25. "Keeping light beams on target," Durie, D. S. L., Mach. Design, p. 128 (Sept. 28, 1967). Mounting and adjustment of reflecting prisms and plane mirrors. Two examples are given. A mirror mount for precise adjustment is described.

5.26. "Floating optical mount," Rayside, John S., and Fletcher, William H., Appl. Opt. 14, 2334 (1975). Details of an optical component mount for precision adjustment.

The final reference here fits none of the above categories but should be included in this section on mounting. Since the integration of a laser into a system poses some special problems and solves others, the mounting of a laser in a system should be treated differently from the passive optical components listed above.

***5.27.** "Integrating Nd:YAG lasers into optical systems," Roberts, D. Allan, in *Optical Systems Engineering,* P. R. Yoder, Jr., ed., Proc. SPIE 193, 121–128 (1979). This is an excellent paper on the factors to be considered in the design of a laser-based optical system. Two examples, a laser rangefinder and a laser machine tool, are used. Optomechanical design, damage problems, and alignment are discussed after a description of the layout.

6. MECHANICAL ANALYSIS

Finite element analysis is a computer-based technique that is used to analyze the response of material masses to mechanical and heat stresses. It is most useful in those problems where a complicated geometry makes a straightforward analytical solution impossible. Programs like NASTRAN and STRUDL are commonly used with this method. The following references provide some information as to how optical information can be derived from such programs. The first reference provides some idea on current practice; the second describes a simple application and gives some idea of the power of the method.

***6.1.** "Finite element methods for evaluating optical system performance," in *Optical Systems Engineering IV,* P. R. Yoder, Jr., ed., Proc. SPIE 518, 145–149 (1985). This paper attempts to give some idea of how the incorporation of ray-trace information in a standard finite-element program (MSC/NASTRAN) can yield performance data that are readily interpretable in optics terms.

6.2. "Elastic deformation of lightweight mirrors," Richard, R. M., and Malvick, A. J., Appl. Opt. 12, 1220 (1973). Report of a finite-element analysis of lightweight mirrors with ribbed structures. An early report on what has become a standard technique in optomechanical analysis.

One can put the subject of vibration isolation within the category of mechanical analysis. In many cases, particularly in a laboratory setting, the problem is "solved" by putting the system on a vibration-isolation table. However, because of cost, weight, and/or volume restrictions, it is not always possible to ship an optical system with a commercial isolation system. A relatively easy to understand text in the field is

6.3. *Seismic Mountings for Vibration Isolation,* Macinante, Joseph A. (Wiley, New York, 1984). An introductory text on vibration isolation that covers basic principles, seismic mountings, and mountings for sensitive equipment.

The following paper is hard to categorize since it describes a whole host of problems and their solutions. It is placed here since it includes a solution to the very nasty problem of isolating a laser optical system from a high velocity nozzle.

***6.4.** "Optical bench for chemical laser testing," Durie, D. S. L., Opt. Eng. 20(4), 625–628 (1981). Although this paper describes a specific optical system, the analysis and techniques to provide vibrational isolation and mechanical adjustment of heavy mirrors are excellent examples of optomechanical design.

7. THERMAL ANALYSIS

Eventually, an optical engineer must worry about the changes in temperature that his or her system will be subjected to. The first question that is asked is, Will temperature affect my system to the point that it will no longer be within specifications? If the answer is yes, then the second question is, How can I compensate for these changes? The next two entries provide basic guidance for the case of uniform temperature changes:

***7.1.** "Thermal effects in optical systems," Jamieson, Thomas H., Opt. Eng. 20(2), 156–160 (1981). Describes variations of optical system parameters with temperature. Provides examples of the effects of uniform temperature increase in seven types of lens systems. Brief discussion of thermal gradients in a single element lens. Earlier version in *Optical Systems Engineering,* P. R. Yoder, Jr., ed., Proc. SPIE 193, 101–107 (1979).

7.2. "Athermalization of optical systems," Grey, D. S., J. Opt. Soc. Am. 38, 543 (1948). "Equations are given for the condition that a focal surface of a lens system remain at a predetermined position for a range of ambient temperatures. Simple methods of satisfying these equations for lens systems composed . . . of plastic components are described" (from abstract).

Perhaps one of the more difficult calculations in the thermal analysis of optical systems is that of computing the effect of radial gradients in the temperature profile of an optical system:

***7.3.** "Design of athermal lens systems," Köhler, H., and Strähle, F. (Proc. 9th Int. Comm. on Optics, Washington, D.C., 1974), p. 116. The problem of radial gradients in a series of lenses is analyzed after a short review of the effects of temperature changes on a system with no thermal gradients. Design of an athermal achromatic doublet for both cases is presented.

***7.4.** "On thermal-optical distortions of glass disks," Mehltretter, J. P., J. Optics (Paris) 10, 93 (1979). Calculations on the thermal deformation of a large lens or window. Although a direct comparison was not made, the calculations were used to estimate a radial temperature difference for a lens in an actual operating environment.

One example of passive thermal compensation by choosing materials and geometries is given in the next reference:

7.5. "Thermo-optical analysis of two long-focal-length aerial reconnaissance lenses," Friedman, Irwin, Opt. Eng. 20(2), 161–165 (1981). Description of the performance of two long focal length lenses at 20 °C and 60 °C. Design of a thermal compensating lens mount to eliminate focus shift by constructing a holder of aluminum and stainless steel between a lens flange and the film plane.

Because of the high thermal expansion coefficients of plastics compared to glasses, special concern must be given to temperature effects upon the design of an optical system containing plastic elements:

***7.6.** "Third-order theory of thermally controlled plastic and glass triplets," Estelle, Lee R., in *1980 International Lens Design Conference,* R. E. Fischer, ed., Proc. SPIE 237, 392–401 (1980). "A paraxial mathematical expression for directly controlling thermal shifts . . . is used to achieve . . . families of thermally controlled triplet solutions. The solutions, depending on the aberration requirements, become finished designs or optimum starting points . . ." (from abstract).

7.7. "Control of thermal focus in plastic-glass lenses," Straw, Kimball, in *1980 International Lens Design Conference,* R. E. Fischer, ed., Proc. SPIE 237, 386–391 (1980). Presents a method of reducing thermal focus shifts in a plastic optical system by incorporating a glass lens in the design and treating thermal shifts as chromatic aberrations by using artificial refractive indices. Two examples, an f/8 triplet and a four-element lens, are analyzed.

The three papers listed below present reports on different problems that can be encountered with mirror systems, from rapid cooling to modest laser power fluxes to overall system prediction:

7.8. "Design and fabrication of aluminum mirrors for a large aperture precision collimator operating at cryogenic temperatures," Fuller, Joseph B. C., Jr., Forney, Paul, and Klug, Carl M., in *Proceedings of the Los Alamos Conference on Optics,* D. H. Liebenberg, ed., Proc. SPIE 288, 104–110 (1981). Description of the design of an optical system with a low thermal mass and rapid cooldown times. The choice of materials, the optomechanical design, and the test of the completed system are given.

7.9. "Balanced thermal deflection approach for beam handling in medium power optical systems," Miller, T. L., and Grigg, R. D., in *Optical Systems Engineering IV,* P. R. Yoder, Jr., ed., Proc. SPIE 518, 150–154 (1985). Powers between 100 mW and 3 W can induce significant distortion of mirrors in an optical system. Several types of mirror designs are analyzed by closed form and finite-element methods to determine the best design to control curvature change and overall temperature rise.

***7.10.** "Predicting performance of optical systems undergoing thermal/mechanical loadings using integrated thermal/structural/optical numerical methods," Miller, Jacob, Hatch, Marcus, and Green, Kenneth, Opt. Eng. 20(2), 166–174 (1981). A number of design/analysis programs are interfaced to provide overall performance prediction of optical systems. The most useful part of this paper is the set of illustrations of error budgeting for four optical systems.

Another field of materials that has had an impact on the design of athermal optical systems is that of composite materials:

***7.11.** "Design of highly stable optical support structure," Krim, Michael H., Opt. Eng. 14(6), 552–558 (1975). Describes the approach and calculations used to design a graphite-epoxy mirror support structure with temperature compensation to provide less than 1 μm focus change in a telescope with 193 inch mirror separation.

8. POSITIONING

Although not directed to the optical engineer, the first three texts here represent sources of information on locating and moving optical components within a system:

8.1. *Fine Mechanisms and Precision Instruments (Principles of Design),* Trylinski, W. (translated from the Polish by A. Vollnagel), (Pergamon Press, Oxford, 1971). Description and equations for precision design covering housings, joints, elastic elements, supports, guides, pins, shafts, couplings, gears, drives, and indicators.

8.2. *Mechanical Engineering Design,* Shigley, Joseph Edward (McGraw-Hill, New York, Third Edition, 1977). A basic text on mechanical engineering in which certain subjects are provided with alternative discussions for the practicing engineer. A few sections include material for the programmable calculator (or, now, the microcomputer).

8.3. *Theory of Machines and Mechanisms,* Shigley, Joseph Edward, and Uicker, John Joseph, Jr. (McGraw-Hill, New York, 1980). After a standard exposition of kinematic analysis, this text describes in detail cams, gears, trains, and linkages that might prove useful to an optical engineer with a difficult scanning or component motion problem.

A short gloss on the above texts is

***8.4.** "How to achieve precise adjustment," Tuttle, Stanley B., Mach. Design, p. 227 (Feb. 16, 1967). Four examples of precise rectilinear positioning and four examples of precise angular positioning are illustrated.

In addition to the precision motion that can be provided by mechanical means, piezoelectric methods are available to the engineer.

8.5. "Advances in submicron positioning," Spanner, Karl, and Marth, Harry, in *Advances in Laser Scanning and Recording,* L. Beiser, ed., Proc. SPIE 396, 80–84 (1983). A brief overview of piezoelectric translators for submicrometer positioning. Discussion of design using these elements is not given. Problems of hysteresis and nonlinearity are not discussed.

Another technique for achieving precise positioning is the use of flexures. These devices are based on shaped materials that use their elasticity to permit controlled deflections. One of the best sources of papers on flexures with equations and examples has been *Machine Design:*

***8.6.** "Flexures," Billig, Victor, Mach. Design, p. 114 (Feb. 4, 1960). A number of different types of flexures are described and illustrated. The design procedure for a transverse circular flexure is outlined, and three graphical solutions to necessary equations are plotted.

***8.7.** "Flexure-pivot bearings (Part 1)," Weinstein, Warren D., Mach. Design, p. 149 (June 10, 1965). First of a two-part paper on flexure pivots. Describes one-, two-, and three-strip bearings. Single-strip bearing equations are given along with an example.

***8.8.** "Flexure-pivot bearings (Part 2)," Weinstein, Warren D., Mach. Design, p. 136 (July 8, 1965). Second of a two-part paper on flexure pivots. Equations and design examples are given for two- and three-strip bearings. Although graphs are given, these are the kind of computations one can now easily program into a microcomputer.

***8.9.** "How to design flexure hinges," Paros, J. M., and Weisbord, L., Mach. Design, p. 151 (Nov. 25, 1965). Describes a number of flexure hinge geometries and the equations that describe the motion. No examples are given.

***8.10.** "Designing springs for parallel motion," Neugebauer, George H., Mach. Design, p. 119 (Aug. 7, 1980). A description of the several types of flexures designed for parallel motion. Equations for the amount of flexure for an applied load are given.

A short note on positioning of an optical instrument is

8.11. "Adjustable instrument mount," Brooks, LeRoy S., J. Opt. Soc. Am. 44, 87 (1954). A half-page description with three figures of a kinematic mount with adjustments.

Small mirror movements and path length changes can be measured using various standard interferometric geometries. One such technique particularly suited to lock-in techniques is analyzed in the following paper:

8.12. "The optical screw as a path difference measurement and control device: analysis of periodic errors," Hopkinson, G. R., J. Optics (Paris) 9, 151 (1978). A diagram of the optical arrangement is given along with an analysis of the sources of periodic errors that crop up in this device.

9. STABILIZATION

A problem optical engineers sometimes face is that after an optical system has been aligned, someone moves it. The stabilization of an image on a detector plane and the steering of a laser beam to keep it on target are problems addressed by these four references:

***9.1.** "Line-of-sight steering and stabilization," Netzer, Yishay, Opt. Eng. 21(1), 96–104 (1982). "This article discusses various methods for steering the line-of-sight of an optical system based on controlling a subsystem or a single optical element. The applicability of some of the methods for line-of-sight stabilization is discussed" (from abstract).

***9.2.** "Image rotation devices — a comparative survey," Swift, D. W., Optics and Laser Technology 4, 175 (1972). "This paper discusses image rotation devices in general terms, and then attempts to collect together the more commonly used devices and to present comparative information on them .... In addition a number of lesser known and novel arrangements are described" (from abstract).

9.3. "A compact derotator design," Durie, D. S. L., Opt. Eng. 13(1), 19–22 (1974). An extensive examination of a simple image derotator. Equations and graphs provide sufficient information to design a derotator for a specific application. Mechanical design of the prism mounting is also discussed.

***9.4.** "Image stabilization techniques for long range reconnaissance camera," Lewis, George R., in *Long Focal Length, High Altitude Standoff Reconnaissance,* D. H. Jarvis, ed., Proc. SPIE 242, 153–158 (1980). Two-axis stabilized mirrors are used to maintain a constant aerial reconnaissance image on a film during flight. Scan equations, design, system layout, and testing are discussed.

10. BAFFLING

The problem of stray light in optical systems is highly dependent on the application. In most cases it involves the detection of faint images in the presence or surround of a bright background. As to its place in optomechanical design, the subject straddles the field with that of optical design. Many papers deal with optical design programs that incorporate stray light calculations but are of little use without access to the programs. The following papers, however, should provide some basic guidance.

***10.1.** "Problems and techniques in stray radiation suppression," Breault, Robert P., in *Stray-Light Problems in Optical Systems,* J. D. Lytle and H. Morrow, eds., Proc. SPIE 107, 2–24 (1977). This paper presents "some basic concepts that the optical and/or mechanical designer can consider when initially designing a sensor system" (from abstract). Probably the most concise description of radiation suppression strategies available in the open literature.

***10.2.** "First-order design of optical baffles," Freniere, Edward R., in *Radiation Scattering in Optical Systems,* G. H. Hunt, ed., Proc. SPIE 257, 19–28 (1981). Basic nomenclature, design techniques, and goals for stray-light reduction are presented.

11. ASSEMBLY AND ALIGNMENT

Since it is impossible to separate assembly of an optical system from its alignment, I have combined the references to these two steps in the completion of an optical design. The part that assembly plays in optomechanical design is fairly obvious, but that of alignment is somewhat subtler. In most cases the provisions for alignment at an early stage of the optomechanical design are necessary to reduce redesign and maintain schedules.

***11.1.** "Concepts and misconceptions in the design and fabrication of optical assemblies," Thorburn, Eugene K., in *Optomechanical Systems Design,* M. Bayar, ed., Proc. SPIE 250, 2–7 (1980). This is a succinct description of the difficulties in fabricating optical components to specification. Practical aspects of radius tolerancing, lens centration tolerancing and measuring, and thickness tolerancing are discussed.

***11.2.** "Methods for the control of centering error in the fabrication and assembly of optical elements," Zaltz, Alexander, and Christo, Douglas, in *Optical Systems Engineering II,* P. R. Yoder, Jr., ed., Proc. SPIE 330, 39–48 (1982). The paper includes calculation of centering error and methods for measuring and controlling centering error. Also includes tables of relationships between error parameters and measurement methods for single elements and complete optical systems.

***11.3.** "Modular design/assembly/alignment approach to an infrared (IR) scanning system," Fischer, Robert E., in *Optical Systems Engineering,* P. R. Yoder, Jr., ed., Proc. SPIE 193, 161–169 (1979). Optomechanical design trade-offs that lead to a modular design of an IR scanning system. Tolerances for fabrication, assembly, and alignment are given, and some assembly and alignment procedures are described. Go/no-go test procedures for modules are also given.

***11.4.** "Incorporation of assembly alignment methods at the design stage of complex optical systems," Fisher, Richard L., in *Optical Systems Engineering II,* P. R. Yoder, Jr., ed., Proc. SPIE 330, 2–4 (1982). A list of considerations to be incorporated early in a design process. Most descriptions are one paragraph long and a few have a simple example. What any good designer ought to know.

Some specific examples of alignment techniques and their relation to the optomechanical design of the system are

11.5. "Alignment design for a cryogenic telescope," Young, Philip, and Schreibman, Martin, in *Optical Alignment,* R. N. Shagam and W. C. Sweatt, eds., Proc. SPIE 251, 171–178 (1980). Incorporation of provisions for alignment into the design of a telescope that had to be built and tested under one set of conditions and used under another set.

11.6. "Alignment of precision lens elements," Hopkins, Robert E., and Walsh, Kenneth F., in *Optical Alignment II,* M. C. Ruda, ed., Proc. SPIE 483, 126–130 (1984). An interferometric technique for mounting elements in a precision lens is described. The chief attraction of this method is that the requirements on edging the elements and machining the barrel are relaxed in favor of parallelism of the barrel mounting surfaces. Alignment is described.

11.7. "Alignment of rotational prisms," Sullivan, D. L., Appl. Opt. 11, 2028 (1972). The optical, mechanical, and rotational axes of prisms used for rotating images (e.g., Dove and Pechan prisms) must all be aligned to prevent a wobbling image. This paper analyzes image movement to provide information on alignment.

***11.8.** "Alignment of off-axis aspheric surfaces," Ruda, Mitchell, in *Optical Alignment,* R. N. Shagam and

W. C. Sweatt, eds., Proc. SPIE 251, 29–36 (1980). Describes the alignment of off-axis aspheric systems, including those systems whose optical parameters are unknown. A wire test and the required autostigmatic cube is described, and examples of shadow patterns are illustrated.

11.9. "Development of a multidetector deflection measurement system," Bissinger, H. D., and Robinson, W. L., in *Optical Alignment II,* M. C. Ruda, ed., Proc. SPIE 483, 24–32 (1984). Describes a series of lenses, beamsplitting cubes, and lateral effect detectors that can be used to monitor the position and tilt of a laser beam. Equations are given for the parameters and the calibration coefficients. The calibration procedure for the sensor is also given.

12. SCANNING

One subfield of optics technology that has blossomed in recent years is scanning. Whether it is scanning an image across a target or scanning a focused laser beam across a photoconductive drum, the design of the mounting and the limitations of the mechanical error found in the motors and bearings are certainly an area of concern to an optical engineer. The first of these references is intended as an introduction to the basics of scanning; the second, a recent overview of the field:

12.1. *Elements of Modern Optical Design,* O'Shea, Donald C. (Wiley, New York, 1985). Elementary textbook on optical design with a chapter on scanners and modulators.

12.2. *Advances in Laser Scanning Technology,* Beiser, Leo, ed., Proc. SPIE 299 (1982).

The next three entries address the problems of scanning motors and the role they play in a system incorporating a scanner:

***12.3.** "Motors and control systems for rotating mirror deflectors," Hayosh, Thomas D., in *Laser Scanning Components and Techniques—Design Considerations/Trends,* L. Beiser and G. F. Marshall, eds., Proc. SPIE 84, 97–108 (1977). A comprehensive review of the types of motors that can be used for scanning applications. A good knowledge of motors is needed since the descriptions are rather terse. A table of motor parameters versus motor types should be helpful in sorting out the various types of motors.

***12.4.** "Design considerations for high performance scanner motors," Koch, Roy A., in *Laser Scanning and Recording,* L. Beiser, ed., Proc. SPIE 498, 54–58 (1984). Explanation of the hysteresis motor and discussion of its electrical and mechanical characteristics. The considerations that go into specifying a scanning motor are explored.

***12.5.** "Technical considerations of rotating mirror deflectors simple and sophisticated," Hayosh, Thomas D., in *Laser Scanning Components and Techniques — Design Considerations/Trends,* L. Beiser and G. F. Marshall, eds., Proc. SPIE 84, 123–133 (1977). Calculation and description of cantilevered and integral mirror-shaft constructions. Parameters to be considered in the design of a rotating mirror deflector are discussed.

Another problem that occurs in scanning systems is that of trying to reduce the inertia of a scanning mirror by making it as thin as possible in order to increase the frequency response of the system. At high tangential velocities, however, these "slenderized" mirrors begin to distort. Two references that address this problem are

***12.6.** "Dynamic mirror distortions in optical scanning," Brosnens, P. J., Appl. Opt. 11, 2987 (1972). Analysis of the deformations that can be expected from thin (small thickness-to-width ratio) rectangular scanning mirrors under high acceleration. This is most applicable to periodic oscillating mirrors, such as galvanometer scanners.

***12.7.** "Deflection of a circular scanning mirror under angular acceleration," Conrad, D. A., Opt. Eng. 14(1), 46–49 (1975). Analysis of a thin circular mirror undergoing angular deformation. All results are given in a dimensionless form so that calculations can be made for a specific combination of any angular acceleration, plate stiffness, density, thickness, and radius.

A different type of scanning application, one involving a large mirror, is described in the next reference:

12.8. "Large scan mirror assembly of the new Thematic Mapper developed for LANDSAT 4 earth resources satellite," Starkus, Charles J., in *Infrared Technology IX,* I. J. Spiro and R. A. Mollicone, eds., Proc. SPIE 430, 85–92 (1983). Description of an ingenious use of "bumpers" to linearize the angular velocity of an oscillating scan mirror between turnaround points.

One type of motor-driven optic is the optical encoder. Although optical encoders are usually taken for granted, in high precision systems their operation and maintenance must be examined.

12.9. "Installation and maintenance of high resolution optical shaft encoders," Breslow, Donald H., in *Photo and Electro-Optics in Range Instrumentation,* W. J. Carrion, J. Cornell, J. E. Durrenberger, and R. Peterson, eds., Proc. SPIE 134, 84–92 (1978). Shaft encoders are usually added to a design as an afterthought. The author "present[s] a thorough review of the mechanical parameters that must be defined and controlled to properly interface a high resolution encoder" (from abstract). Maintenance techniques are also discussed.

There are probably additional subjects that could be included under the umbrella "optomechanical design" but the above fields are the ones I have found most important in my own work. I would appreciate any comments, criticisms, or notices of omissions. (Please remember, however, that many of my omissions were deliberate, as noted in the introduction.)

In my conversations with many people practicing optical engineering, it is obvious that the subject of optomechanical design has been considered an ancillary subject that is many times addressed after the fact. But as the field of optics grows and the systems become more complex, I expect to see many of these isolated subjects incorporated into the design process at earlier stages, reducing the need for "fixes" in an optical design. It will make for some exciting and rewarding times for those who pay attention to putting their optical design down in the real world.

13. ACKNOWLEDGMENTS

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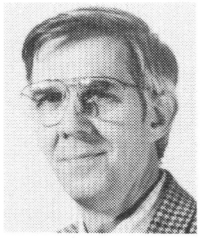

Donald C. O'Shea received his B.S. degree in physics from the University of Akron (Ohio) in 1960 and his M.S. degree in physics from Ohio State University in 1963. After obtaining his Ph.D. degree in physics from Johns Hopkins University in 1968 he was a postdoctoral fellow at Gordon McKay Laboratories at Harvard University. Since 1970 he has been on the faculty of the School of Physics at the Georgia Institute of Technology, where he is now an Associate Professor and Coordinator of the Applied Optics program. For the past seven years he has been the principal lecturer of a course, Laser System Design, given twice a year at the University of Wisconsin Extension. His current interests are in the fields of electro-optics, optical physics, optical engineering, especially optomechanical design, and optics education. He is the coauthor with W. T. Rhodes and W. R. Callen of *Introduction to Lasers and Their Applications* (Addison-Wesley, 1977) and author of *Elements of Modern Optical Design* (Wiley, 1985). He has been a member of several OSA and SPIE committees on education and chaired the SPIE Education Committee in 1984. Dr. O'Shea is a member of OSA and a Fellow of SPIE.