Integrated Optomechanical Analysis

SECOND EDITION

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SPIE PRESS
Bellingham, Washington USA

Library of Congress Cataloging-in-Publication Data

Doyle, Keith B.
Integrated optomechanical analysis, second edition / Keith B. Doyle, Victor L. Genberg, Gregory J. Michels
p. cm.
Includes bibliographical references and index.
ISBN 9780819492487
1. Optical instruments–Design and construction. I. Genberg, Victor L. II. Michels, Gregory J. III. Title.

Library of Congress Control Number: 2012943824

Published by

SPIE—The International Society for Optical Engineering
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Bellingham, Washington 98227-0010 USA
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Email: spie@spie.org
Web: http://spie.org

Printed in the United States of America.
First printing

SPIE

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Introduction

Optomechanical engineering is the application of mechanical engineering principles to design, fabricate, assemble, test, and deploy an optical system that meets performance requirements in the service environment. The challenge of optomechanical engineering lies in preserving the position, shape, and optical properties of the optical elements with specified tolerances typically measured in microns, microradians, and fractions of a wavelength.

Optomechanical analyses are an integral part of the optomechanical engineering discipline to simulate the mechanical behavior and performance of the optical system. These analyses include a broad range of thermal, structural, and mechanical analyses that support the design of optical mounts, metering structures, mechanisms, test fixtures, and more. This includes predicting the performance, dimensional stability, and structural integrity of optomechanical designs subject to internal mechanical loads and often harsh environmental disturbance, including inertial, pressure, thermal, and dynamic disturbance. Designs must provide for positive margin against failure modes that include yielding, buckling, ultimate failure, fatigue, and fracture.

Analysis starts with first-order estimates using analytical solutions based on classic elasticity and heat transfer theory. These closed-form solutions provide rapid estimates of structural and thermal behavior and an understanding of the governing parameters controlling the response. Finite element analysis (FEA) methods are widely used to provide more-accurate and higher-fidelity mechanical response predictions. Models of varying complexity may be developed by discretizing the structure into one-, two-, or three-dimensional elements to meet both efficiency and accuracy requirements. Thermal analysis models use both finite element methods and finite difference techniques to predict the thermal behavior of optical systems. Models are developed to predict thermal response quantities such as temperature distributions and heat fluxes that account for conduction, convection, and radiation modes of heat transfer.

Integrated optomechanical analysis involves the coupling of the structural, thermal, and optical simulation tools in a multi-disciplinary process commonly referred to as structural-thermal-optical performance or STOP analyses. The benefit of performing integrated analyses is the ability to provide insight into the interdisciplinary design relationships of thermal and structural designs and their impact through a deterministic assessment of optical performance. Engineering decisions during both the conceptual and execution stages of a program can then be based on high-fidelity performance simulations that are combined with program performance and reliability requirements, risk tolerance, schedule, and cost objectives to optimize the overall system design.

Integrated optomechanical analyses benefit optical system concept development by providing a rigorous and quantitative evaluation to explore the mission and design-trade spaces. The benefits of a wide variety of optical design configurations can be evaluated to account for factors such as the mechanical design, pointing control and stability, thermal management, and materials selection for architecture down select.

During the execution stages of a program, integrated optomechanical analyses capture complex environmental conditions and concurrent disturbances. These analyses can be performed to compute performance as a function of time such as during operational scenarios that provide insights beyond which can be captured by a roll-up of static error-budget contributions. The simulations can be used in conjunction with numerical algorithms to optimize the design, serve as a predictive test bed for system-performance predictions, or provide for diagnostic evaluations of systems underperforming in the field.

The development and use of integrated optomechanical analyses has significantly increased over the past decade to support the ever-increasing challenges in optical system design, leveraging advances in computational resources. Government organizations have employed integrated tools in support of large-scale programs and advanced technologies, including space- and ground-based telescopes and high-powered beam systems. In addition, commercial organizations have sought to improve their effectiveness and efficiency in the design of optical systems through the application and development of custom-integrated optomechanical software tools. A variety of commercial software has been developed to provide an integrated analysis capability to the broader community.

Several approaches have been taken to integrate or couple the thermal, structural, and optical modeling tools. The "bucket brigade" approach relies on scripts to format and pass data between software tools. The "wrapper" approach uses custom-developed software to automate the data-sharing process. Fully integrated software tools offer the ability to model each discipline in a single, stand-alone modeling environment. Each of these approaches has its advantages and disadvantages, and one may be more appropriate over another for a given application or organization.

An essential piece of successful optomechanical analyses is the verification and validation of the models. Verification may be considered as the assessment of the numerical correctness of the model, i.e., ensuring that the models and the software do not have errors. Analytical solutions, stick models, check-out runs, and crawl-walk-run strategies are all verification methods to help ensure that a model is sound.

Validation may be considered as the assessment of how well the model represents the physical behavior of the hardware. Model validation via testing is performed at various stages of a design cycle. Early testing at the component and subassembly level can be used to validate basic physics and model uncertainties. System-level validation supports requirements verification and provides confidence in analyses that are used to extrapolate performance outside of a limited test domain.

This book serves as a compilation of many of the analyses and integrated methods that the authors have employed and developed in their collective experience supporting the development of optical systems. There are 14 chapters that address key aspects of optomechanical analysis, including the detailed use of FEA methods and techniques to integrate and couple the thermal, structural, and optical analysis tools. There are additional disciplines involved in optical system engineering that may also be incorporated in a broader integrated analysis process that includes controls, radiometry, stray light, and aerodynamics, whose discussions are beyond the scope of this text.

Chapter 1 starts with an introduction to mechanical analysis using finite element methods and considerations in the integration of thermal, structural, and optical analyses. Included is a review of mechanical engineering basics, an overview of materials commonly used in optical systems, and finite element theory. A section on FEA modeling checks is presented that underscores the importance of verifying models and analyses.

Chapter 2 presents the fundamentals of optics, common optical performance metrics, and image formation. Included are discussions on polarized light, diffraction, conic surfaces, the impact of mechanical obscurations on optical performance, and optical system error budgets. This chapter serves as the basis of how mechanical perturbations, including optical surface errors and index of refraction changes due to temperature and stress, affect the performance of optical systems.

Chapter 3 provides an overview of Zernike polynomials and their utility in representing discrete data such as finite element results and as a means of data transfer from the thermal and structural tools into optical design software. Other relevant polynomial forms are also discussed.

Chapter 4 presents optical-surface-error analyses and methods to predict optical performance that account for FEA-derived optical surface errors. Two methods using optical sensitivity coefficients are discussed to predict wavefront error as a function of both rigid-body errors and higher-order elastic surface deformations. Use of optical sensitivity coefficients are beneficial early in the design stages for "closed-loop" analyses that allow mechanical engineers to predict optical performance as a function of mechanical design variables and account for the effects of environmental disturbances. The integration of FEA-derived optical surface errors within commercially available optical design software enables the development of a "perturbed" optical model, from which the full range of optical simulations and performance evaluations may be exercised to assess thermal and structural effects.

Chapters 5 and 6 discuss finite element model construction and analysis methods for predicting displacements of optical elements and support structures. Specific topics include modeling methods for individual optical components, various techniques to model lightweight mirrors, methods to create powered optical surfaces, use of symmetry for efficient modeling practices, and methods to analyze the effects of a variety of surface coating effects. Chapter 6 introduces kinematic mounting principles and focuses on the modeling of optical mounts, adhesive bonds, flexures, test supports, and the use of Monte Carlo methods to evaluate the effects of optical mount misalignments.

For many of the topics discussed in Chapters 5 and 6, analysis and modeling approaches range from first-order to detailed, high-fidelity simulations. The engineer may adopt an analysis strategy where the model fidelity maps to design maturity and requirements accuracy. Low-fidelity models are performed early in the design stages for the “80% solution.” These models are easily modified as the design evolves to support design trades and sensitivity studies. High-fidelity models that are more time consuming to build, modify, run, and post-process can be developed when the design has matured to provide high accuracy.

Chapter 7 provides an overview of structural dynamics, including normal modes, damping, harmonic, random, vibro-acoustic, and shock analyses. Analysis techniques are presented to predict pointing errors and LOS jitter using FEA and optical sensitivity coefficients, including the subsequent impact on optical system performance. Strategies and techniques to reduce the LOS jitter, including the identification of critical modes in the mechanical structure, the use of passive and active stabilization techniques, and the impact of sensor integration time, are included in the discussion. For large-aperture optical systems, methods are presented to predict optical surface distortions and wavefront error due to dynamic excitation of the optical surfaces.

Chapter 8 focuses on mechanical stress. Stress needs to be managed for several reasons in an optical system including structural integrity where excessive stress can lead to permanent misalignments or structural failure of optical elements, mounts, and support structures. An introduction to stress analysis using FEA is presented along with methods to predict the design strength of optical glass. The latter half of Chapter 8 describes the phenomenon of stress birefringence and presents analysis techniques to account for the effects of mechanical stress on optical performance. First-order estimates are provided using the photo-elastic equations along with more involved methods to compute optical performance metrics such as retardance and polarization errors due to complex mechanical stress states.

Chapter 9 presents optothermal analysis methods, including thermo-elastic and thermo-optic modeling techniques. This class of analyses helps drive thermal management strategies used to preserve optical-element surface errors and index-of-refraction changes in the presence of temperature changes. Methods to compute externally derived OPD maps using interferogram files and phase surfaces along with techniques to map temperatures between thermal and structural models that have varying mesh densities are presented. This latter process is a critical step in the STOP modeling effort and is often a technical challenge for program teams. Additional topics include a discussion on bulk volumetric absorption and the use of thermal analysis software to perform analogous analyses, including moisture effects and adhesive curing.

Chapter 10 provides an introduction to the analysis of adaptive optics. Adaptive optic concepts and definitions, including correctability and influence functions, are discussed along with the mathematics to compute actuator motion to minimize optical surface deformations. Practical details on adaptive optics are discussed, including predicting residual surface errors due to actuator failure, stroke limits, resolution, and tolerancing are also presented. Examples are provided on the design of adaptive optics and actuator placement using design optimization methods. Additional topics in the chapter include stress-optic polishing and the use of adaptive tools to solve an analogous class of problems. This latter topic utilizes the same mathematical process for determining actuator inputs to predict the combination of a set of predefined disturbances to best match any arbitrary surface error. Examples are presented that solve for the combination of mount distortions and CTE variations to match interferometric test data.

Chapter 11 discusses structural optimization theory and applications. Numerical optimization consists of powerful techniques that enable a more-efficient evaluation of a broad design space beyond which may be evaluated via parametric design trades. The chapter discusses the use of optical performance metrics in structural optimization simulations and also provides a general discussion on multidisciplinary optimization.

Chapter 12 presents the use of FEA substructuring techniques for optical systems. The use of substructuring or superelements provides many benefits in detailed FEA simulations to provide for a more rapid turnaround of results for greater insight and impact. Superelement theory is presented along with common types of superelements. Examples of modeling kinematic mounts and segmented optical systems using superelements are presented.

The final two chapters present examples of the optomechanical and integrated analyses discussed in the previous chapters. Chapter 13 addresses a variety of analyses on a reflective telescope, and Chapter 14 details the integrated optomechanical analysis of two lens assemblies.

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October 2012