The Computer Aided Engineering Design Series

Design Theory and Methods using CAD/CAE

KUANG-HUA CHANG

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Design Theory and Methods using CAD/CAE

To my best friends in Oklahoma, James and Qin-Fang Chen (陳壽祥、周秦芳), Tony and Freda Chen (陳列、賴慧慈), Fred and Binro Lee (李南海、何濱洛), Victor and Jill Chen (陳功、簡樸珍), and Jaffee Wu (吳繼凱). You are a blessing sent from above to guide and support me. I am truly honored and grateful for the precious friendships and many years of happiness you all have brought to me.

Preface

The conventional product development process employs a design–build–test philosophy. The sequentially executed product development process often results in a prolonged lead time and an elevated product cost. The e-Design paradigm presented in the *Computer Aided Engineering Design* series employs IT-enabled technology, including computer-aided design, engineering, and manufacturing (CAD/CAE/CAM) tools, as well as advanced prototyping technology to support product design from concept to detailed designs, and ultimately manufacturing. This e-Design approach employs virtual prototyping (VP) technology to support a cross-functional team in analyzing product performance, reliability, and manufacturing costs early in the product development stage and in conducting quantitative trade-offs for design decision making. Physical prototypes of the product design are then produced using rapid prototyping (RP) technique mainly for design verification. The e-Design approach holds potential for shortening the overall product development cycle, improving product quality, and reducing product cost. The *Computer Aided Engineering Design* series intends to provide readers with a comprehensive coverage of essential elements for understanding and practicing the e-Design paradigm in support of product design, including design method and process, and computer-based tools and technology. The book series consists of four modules: *Product Design Modeling Using CAD/CAE*, *Product Performance Evaluation Using CAD/CAE*, *Product Manufacturing and Cost Estimating Using CAD/CAE*, and *Design Theory and Methods Using CAD/CAE*. The *Product Design Modeling Using CAD/CAE* book discusses virtual mockup of the product that is first created in the CAD environment. The critical design parameterization that converts the product solid model into parametric representation, enabling the search for better designs, is an indispensable element of practicing the e-Design paradigm, especially in the detailed design stage. The second book, *Product Performance Evaluation Using CAD/CAE*, focuses on applying numerous computer-aided engineering (CAE) technologies and software tools to support evaluation of product performance, including structural analysis, fatigue and fracture, rigid body kinematics and dynamics, and failure probability prediction and reliability analysis. The third book, *Product Manufacturing and Cost Estimating Using CAD/CAE*, introduces computer-aided manufacturing (CAM) technology to support manufacturing simulations and process planning, RP technology and computer numerical control (CNC) machining for fast product prototyping, as well as manufacturing cost estimate that can be incorporated into product cost calculations. The product performance, reliability, and cost calculated can then be brought together to the cross-functional team for design trade-offs based on quantitative engineering data obtained from simulations. Design trade-off is one of the key topics included in the fourth book, *Design Theory and Methods Using CAD/CAE*. In addition to conventional design optimization methods, the fourth book discusses decision theory, utility theory, and decision-based design. Simple examples are included to help readers understand the fundamentals of concepts and methods introduced in this book series.

In addition to the discussion on design principles, methods, and processes, this book series offers detailed review on the commercial off-the-shelf software tools for the support of modeling, simulations, manufacturing, and product data management and data exchanges. Tutorial style lessons on using commercial software tools are provided together with project-based exercises. Two suites of engineering software are covered: they are Pro/ENGINEER-based, including Pro/MECHANICA Structure, Pro/ENGINEER Mechanism Design, and Pro/MFG; and SolidWorks-based, including

SolidWorks Simulation, SolidWorks Motion, and CAMWorks. These tutorial lessons are designed to help readers gain hands-on experiences to practice the e-Design paradigm.

The book you are reading, *Design Theory and Methods Using CAD/CAE*, is the fourth (last) module of the *Computer Aided Engineering Design* series. The objective of the *Design Theory and Methods* book is to provide readers with fundamental understanding in product design theory and methods, and apply the theory and methods to support engineering design applications in the context of e-Design. In Chapter 1, a brief introduction to the e-Design paradigm and tool environment will be given. Following this introduction, important topics in design theory and methods, including decision methods and theory in engineering design, design optimization, structural design sensitivity analysis, as well as multi-objective design optimization will be discussed.

Chapter 2 focuses on decision making for engineering design, in which conventional decision methods and decision theory, as well as decision-based design developed recently are discussed. The conventional methods, such as decision tree and decision table, have been widely employed by industry in support of design decision making. On the other hand, decision theory offers scientific and theoretical basis for design decision making, which gained attentions of researchers in recent years. This chapter offers a short review on popular decision methods, design theory, as well as the application of the theory to support engineering design. This chapter serves as a prelude to chapters that follow.

Chapter 3 discusses design optimization, which is one of the mainstream methods in engineering design. We discuss linear and nonlinear programming and offer mathematical basis for design problem formulation and solutions. We include both gradient-based and non-gradient approaches for solving optimization problems. In this chapter, readers should see clearly the limitations of the non-gradient approaches in terms of the computational efforts of the design problems, especially, large-scale problems. The gradient-based approaches are more suitable to the typical problems in the context of e-Design. We focus on single-objective optimization that serves the basis to understand multiobjective optimization to be discussed in Chapter 5 that is much relevant to practical applications. We address issues involved in dealing with practical engineering design problems and discuss an interactive design approach, including design trade-off and what-if study, which is more suitable for support of large-scale design problems. We offer case studies to illustrate practical applications of the methods discussed and a brief review on software tools that are commercially available for support of various types of optimization problems.

Chapter 4 provides a brief discussion on the sensitivity analysis, that is, gradient calculations that are essential for design using the gradient-based methods. In this chapter, we narrow our focus on structural problems in hope to introduce basic concept and methods in gradient calculations. We include in this chapter popular topics, such as sizing, shape, and topology designs. We also offer case studies to illustrate practical applications of the methods discussed. Some aspect of the ideas and methods on gradient calculations for structural problems can be extended to support other engineering disciplines; for example, motion and machining time. Two case studies are presented to illustrate a practical scenario that involves integration of topology and shape optimization and an advanced topic that supports shape design for crack propagation at the atomistic level using multiscale simulations.

In Chapter 5, we introduce multiobjective design optimization concept and methods. We start with simple examples to illustrate the concept and introduce Pareto optimality. We then discuss major solution techniques categorized by the articulation of preferences. We also include multiobjective genetic algorithms that gain popularity in recent years. In addition, we revisit decision-based design

using both utility theory and game theory introduced in Chapter 3. We make a few comments on the decision-based design approach from the context of multiobjective optimization. We include a discussion on software tools that offer readers knowledge on existing tools for adoption and further investigation. We also include two advanced topics, reliability-based design optimization and design optimization for product manufacturing cost.

In addition to theories and methods, two companion projects are included: *Project S5 Design with SolidWorks* and *Project P5 Design with Pro/ENGINEER*. These projects offer tutorial lessons that should help readers to learn and be able to use the respective software tools for support of practical design applications. We include two examples in each projects, design optimization of a cantilever beam, and multidisciplinary design optimization for a single-piston engine. Example files needed for going through the tutorial lessons are available for download at the book's companion site. The goal of the projects is to help readers become confident and competent in using CAD/CAE/CAM and optimization tools for creating adequate product design model and adopt effective solution techniques in carrying out product design tasks.

This *Design Theory and Methods* book should serve well for a half semester (8 weeks) instruction in engineering colleges of general universities. Typically, a three-hour lecture and one-hour laboratory exercise per week are desired. This book (and the book series) aims at providing engineering senior and first-year graduate students a comprehensive reference to learn advanced technology in support of engineering design using IT-enabled technology. Typical engineering courses that the book serves include Computer-Aided Design, Engineering Design, Integrated Product and Process Development, Concurrent Engineering, Design and Manufacturing, Modern Product Design, Computer-Aided Engineering, as well as Senior Capstone Design. In addition to classroom instruction, this book should support practicing engineers who wish to learn more about the e-Design paradigm at their own pace.

About the Author

Dr. Kuang-Hua Chang is a *David Ross Boyd Professor* and *Williams Companies Foundation Presidential Professor* at the University of Oklahoma (OU), Norman, Oklahoma. He received his diploma in Mechanical Engineering from the National Taipei Institute of Technology, Taiwan, in 1980; and M.S. and Ph.D. degrees in Mechanical Engineering from the University of Iowa, Iowa City, Iowa, in 1987 and 1990, respectively. Since then, he joined the Center for Computer-Aided Design (CCAD) at Iowa as a Research Scientist and CAE Technical Area Manager. In 1997, he joined OU. He teaches mechanical design and manufacturing, in addition to conducting research in computer-aided modeling and simulation for design and manufacturing of mechanical systems.

His work has been published in 7 books and more than 150 articles in international journals and conference proceedings. He has also served as technical consultants to US industry and foreign companies, including LG-Electronics, Seagate Technology, and so forth. Dr. Chang received numerous awards for his teaching and research in the past few years, including the Williams Companies Foundation presidential professorship in 2005 for *meeting the highest standards of excellence in scholarship and teaching*, OU Regents Award for Superior Accomplishment in Research and Creative Activity in 2004, OU BP AMOCO Foundation Good Teaching Award in 2002, and OU Regents Award for Superior Teaching in 2010. He is a five-time recipient of CoE Alumni Teaching Award, given to top teachers in CoE. His research paper was given a Best Paper Award at the iCEER-2005 iNEER Conference for Engineering Education and Research in 2005. In 2006, he was awarded a Ralph R. Teetor Educational Award by SAE *in recognition of significant contributions to teaching, research and student development*. Dr. Chang was honored by the OKC Mayor's Committee on Disability Concerns with the 2009 Don Davis Award, which is *the highest honor granted in public recognition of extraordinarily meritorious service which has substantially advanced opportunities for people with disabilities by removing social, attitudinal, & environmental barriers in the greater Oklahoma City area.* In 2013, Dr. Chang was named David Ross Boyd Professor, one of the highest honors at the University of Oklahoma, for *having consistently demonstrated outstanding teaching, guidance, and leadership for students in an academic discipline or in an interdisciplinary program within the University.*

About the Cover Page

The cover page shows the solid model of an airplane torque tube in computer that is one of the three similar tubes located in the front leading edge of the wing, three on each side. These torques tubes were re-engineered for enhanced product reliability and reduced manufacturing lead-time. The problems are twofold. First, the current magnesium tubes designed decades ago suffer poor corrosion-resistance, requiring frequent repairs. Second, magnesium tubes are made by casting, which is extremely uneconomical when used for producing a very small quantity required for the remaining aircraft fleet. Lead-times were excessive and the cost was extremely high for acquiring the tubes. Involving the original equipment manufacturer (OEM) in re-engineering the torque tubes has also proven to be cost prohibitive. Therefore, without the original technical data package, sample tubes are first measured for critical geometric dimensions using a coordinate measurement machine (CMM). The measurement data are employed for constructing parametric solid models using a CAD system, in this case, Pro/ENGINEER. Once the parametric solid model is available, the product and process re-engineering activities are conducted concurrently. In re-engineering the tubes, strength analyses are conducted for both magnesium and aluminum solid models. In order to reduce the weight of the aluminum tube while maintaining its strength, the tube geometry is changed using a design optimization method (see advanced topic section in Chapter 5 for more details). A sample aluminum tube has been machined at OU and delivered to an Air Force Depot for form, fit checking, and material strength test. The aluminum tube is both stronger and more corrosion-resistant than the magnesium tube it will replace. Machining the tubes using CNC is more cost effective (50% cost reduction), and, more importantly, the manufacturing lead-time is reduced from about 18 months to just one week.

Acknowledgment

I would like to first thank Mr Joseph P. Hayton for recognizing the need of such an engineering design book series that offers knowledge in modern engineering design principles, methods, and tools to mechanical engineering students. His enthusiasm in moving the book project forward and eventually publishing the book series is highly appreciated. Mr Hayton's colleagues at Elsevier, Ms Lisa Jones and her production team, and Ms Chelsea Johnson, have made significant contributions in transforming the original manuscripts into a well-organized and professionally polished book that is suitable and presentable to our readers.

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CHAPTER

INTRODUCTION TO e-DESIGN

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CHAPTER OUTLINE

Design Theory and Methods using CAD/CAE.