

---

# STANDARD HANDBOOK OF MACHINE DESIGN

---

**Joseph E. Shigley** Editor in Chief

*Late Professor Emeritus  
The University of Michigan  
Ann Arbor, Michigan*

**Charles R. Mischke** Editor in Chief

*Professor Emeritus of Mechanical Engineering  
Iowa State University  
Ames, Iowa*

**Thomas H. Brown, Jr.** Editor in Chief

*Faculty Associate  
Institute for Transportation Research and Education  
North Carolina State University  
Raleigh, North Carolina*

**Third Edition**

**McGRAW-HILL**

New York Chicago San Francisco Lisbon London  
Madrid Mexico City Milan New Delhi San Juan  
Seoul Singapore Sydney Toronto

**Cataloging-in-Publication Data is on file with the Library of Congress.**

Copyright © 2004, 1996 by The McGraw-Hill Companies, Inc. All rights reserved. Printed in the United States of America. Except as permitted under the United States Copyright Act of 1976, no part of this publication may be reproduced or distributed in any form or by any means, or stored in a data base or retrieval system, without the prior written permission of the publisher.

1 2 3 4 5 6 7 8 9 0 DOC/DOC 0 9 8 7 6 5 4

ISBN 0-07-144164-6

*The sponsoring editor for this book was Kenneth McCombs, the editing supervisor was Caroline Levine, and the production supervisor was Pamela Pelton. It was set in Times Roman by North Market Street Graphics.*

*Printed and bound by RR Donnelley.*

McGraw-Hill books are available at special quantity discounts to use as premiums and sales promotions, or for use in corporate training programs. For more information, please write to the Director of Special Sales, McGraw-Hill, Professional Publishing, Two Penn Plaza, New York, NY 10121-2298. Or contact your local bookstore.

Information contained in this work has been obtained by The McGraw-Hill Companies, Inc. ("McGraw-Hill") from sources believed to be reliable. However, neither McGraw-Hill nor its authors guarantees the accuracy or completeness of any information published herein and neither McGraw-Hill nor its authors shall be responsible for any errors, omissions, or damages arising out of use of this information. This work is published with the understanding that McGraw-Hill and its authors are supplying information but are not attempting to render engineering or other professional services. If such services are required, the assistance of an appropriate professional should be sought.



This book is printed on recycled, acid-free paper containing 10% postconsumer waste.

---

# CONTRIBUTORS

---

- Thomas H. Brown, Jr.** *Faculty Associate, Institute for Transportation Research and Education, North Carolina State University, Raleigh, N.C. (CHAP. 1)*
- R. B. Bhat** *Associate Professor, Department of Mechanical Engineering, Concordia University, Montreal, Quebec, Canada (CHAP. 31)*
- Sachindranarayan Bhaduri** *Associate Professor, Mechanical and Industrial Engineering Department, The University of Texas at El Paso, El Paso, Tex. (CHAP. 39)*
- John H. Bickford** *Retired Vice President, Manager of the Power-Dyne Division, Raymond Engineering Inc., Middletown, Conn. (CHAP. 22)*
- Omer W. Blodgett** *Design Consultant, The Lincoln Electric Company, Cleveland, Ohio (CHAP. 26)*
- Daniel M. Curtis** *Senior Mechanical Engineer, NKF Engineering, Inc., Arlington, Va. (CHAP. 7)*
- Daniel E. Czernik** *Director of Product Engineering, Fel-Pro Inc., Skokie, Ill. (CHAP. 25)*
- Joseph Datsko** *Professor of Mechanical Engineering Emeritus, The University of Michigan, Ann Arbor, Mich. (CHAP. 32)*
- Raymond J. Drago** *Senior Engineer, Advanced Power Train Technology, Boeing Vertol, Philadelphia, Pa. (CHAP. 10)*
- K. S. Edwards** *Professor of Mechanical Engineering, The University of Texas at El Paso, Tex. (CHAP. 12)*
- Rudolph J. Eggert** *Associate Professor of Mechanical Engineering, University of Idaho, Boise, Idaho (CHAP. 13)*
- Wolfram Funk** *Professor, Fachbereich Maschinenbau, Fachgebiet Maschinenelemente und Getriebetechnik, Universität der Bundeswehr Hamburg, Hamburg, Germany (CHAP. 14)*
- Richard E. Gustavson** *Technical Staff Member, The Charles Draper Laboratory, Inc., Cambridge, Mass. (CHAP. 3)*
- Harry Herman** *Professor of Mechanical Engineering, New Jersey Institute of Technology, Newark, N.J. (CHAP. 30)*
- R. Bruce Hopkins** *The Hopkins Engineering Co., Cedar Falls, Iowa (CHAP. 21)*
- Robert J. Hotchkiss** *Director, Gear Technology, Gleason Machine Division, Rochester, N.Y. (CHAP. 11)*
- Robert E. Joerres** *Applications Engineering Manager, Associated Spring, Barnes Group Inc., Bristol, Conn. (CHAP. 6)*
- Harold L. Johnson** *Associate Professor Emeritus, School of Mechanical Engineering, Georgia Institute of Technology, Atlanta, Ga. (CHAP. 5)*
- Theo J. Keith, Jr.** *Professor and Chairman of Mechanical Engineering, University of Toledo, Toledo, Ohio (CHAP. 19)*
- Theodore K. Krenzer** *Director of Research and Development, Gleason Machine Division, Rochester, N.Y. (CHAP. 11)*

- A. R. Lansdown** *Director, Swansea Tribology Centre, University of Swansea, United Kingdom. (CHAP. 20)*
- Kenneth C. Ludema** *Professor of Mechanical Engineering, Department of Mechanical Engineering and Applied Mechanics, The University of Michigan, Ann Arbor, Mich. (CHAP. 34)*
- Charles R. Mischke** *Professor of Mechanical Engineering Emeritus, Iowa State University, Ames, Iowa. (CHAPS. 17, 18, 27, 28, 29, 33, 37)*
- Andrzej A. Olędzki** *Professor Emeritus, Warsaw Technical University, Warsaw, Poland (CHAP. 4)*
- Richard S. Sabo** *Manager, Educational Services, The Lincoln Electric Company, Cleveland, Ohio (CHAP. 26)*
- T. S. Sankar** *Professor and Chairman, Department of Mechanical Engineering, Concordia University, Montreal, Quebec, Canada. (CHAP. 31)*
- Howard B. Schwerdlin** *Engineering Manager, Lovejoy, Inc., Downers Grove, Ill. (CHAP. 16)*
- Joseph E. Shigley** *Professor Emeritus, The University of Michigan, Ann Arbor, Mich. (CHAPS. 9, 23, 24, 27, 28, 36, 38, Appendix)*
- L. E. Torfason** *Professor of Mechanical Engineering, University of New Brunswick, Fredericton, New Brunswick, Canada (CHAP. 2)*
- Milton G. Wille** *Professor of Mechanical Engineering, Brigham Young University, Provo, Utah. (CHAP. 35)*
- John L. Wright** *General Product Manager, Diamond Chain Company, Indianapolis, Ind. (CHAP. 15)*
- John R. Zimmerman** *Professor of Mechanical and Aerospace Engineering, University of Delaware, Newark, Del. (CHAP. 8)*

---

# FOREWORD

---

Machines evolve. Not biologically, of course, but they evolve nonetheless, from a fragment of an idea or dream to a fully functional mechanical marvel—at least in the eyes of the designer. Machine design is one of the most rewarding activities to which a person can contribute; it is incredibly complex. For some designers, their unique and magical designs, or machine elements, have become a legacy for future generations.

For most of us who are engineers, we will likely not leave a design legacy; but the joy in using what others have devised can be intoxicating. One design project leads to another, and that project leads to yet another. While this process can be hectic, sometimes at the mercy of a difficult schedule, in the end you are proud—proud of what you have done in meeting the design requirements, proud to have met the schedule, and proud of how you have used the seemingly endless variety of machine design elements available to you.

The purpose of the *Standard Handbook of Machine Design* has been, from its inception, to provide the mechanical designer, within in a single reference, the most comprehensive and up-to-date information about what is available and how to utilize it effectively and efficiently. The original authors, Joseph E. Shigley and Charles R. Mischke, two of the most well-known and respected individuals in the mechanical engineering community, assembled experts in every field of machine design: mechanisms and linkages, cams, gear trains, springs, flywheels, clutches, brakes, gear designs of every type, belts, chains, couplings, design of shafts, all manner of roller bearings, journal bearings, lubrication selection, bolts and mechanical fasteners, welding, failure analysis, vibration, performance of engineering materials, wear, corrosion, and classical stress and deformation calculations. This incredible wealth of information, which would otherwise have to be researched in dozens of books and hundreds of scientific and professional papers, was organized by these experts into distinct chapters, as many as 50 in the Second Edition. Here in the Third Edition, the 39 chapters have been grouped into nine broad topic areas of related material. Each chapter stands on its own and, for the veteran designer, provides direct access to a specific area of interest or need.

The *Standard Handbook of Machine Design* is a unique reference, capturing the breadth and depth of what we know and trust. May what you discover and apply from these pages contribute to a successful design, one that will delight not only the designer but those who ultimately find value and long service in the machine that has evolved.

*Thomas H. Brown, Jr.*

---

# PREFACE TO THIRD EDITION

---

This Third Edition of the *Standard Handbook of Machine Design* has been completely reorganized as compared to its two previous editions. To bring into focus the needs of the machine design engineer, without the distractions of ancillary material, the number of chapters has been reduced from 50 in the Second Edition to 39. These 39 chapters have been carefully grouped into nine distinct sections, denoted as Parts 1 through 9. These chapter groupings were inspired primarily by a set of eight “Machine Design Workbooks,” containing much of the material in the First Edition, and published between the First and Second Editions.

After a new introductory chapter, “Evolution of a Successful Design,” the first of nine sections, Part 1, “Machine Elements in Motion,” presents four chapters on the seemingly endless ways to achieve a desired motion. *Kinematics*, or the geometry of motion, is probably the most important step in the design process, as it sets the stage for many of the other decisions that will be made as a successful design evolves. Whether it’s a self-locking latch you are looking for, a complex cam shape, or an entire gear assembly, the information you need is here in these chapters.

Part 2, “Machine Elements that Absorb and Store Energy,” contains three chapters presenting the classic machine elements: springs, flywheels, clutches, and brakes. Not all designs will have a need for these energy-related devices, but, when appropriate, no other device will do the job.

Part 3, “Gearing,” contains five chapters covering every possible gear type, from basic spur gears to complex hypoid bevel gears sets; the intricacies of worm gearing; and the very versatile and relatively modern power screw designs.

Part 4, “Power Transmission,” contains four chapters directed at the requirements of transferring motion from one rotating axis to another, whether by time-honored belt or chain configurations, or the wide variety of couplings used to isolate and protect downstream machine elements. This is also where the design of shafts, from both a static and dynamic viewpoint, is included.

Part 5, “Bearings and Lubrication,” pulls together in one place the design of many types of roller bearings as well as the design aspects of the classic journal bearing. Bearings could not do their job without lubrication, and lubrication would be lost from most bearings without the proper seals. Traditional and nontraditional designs are presented.

Part 6, “Fastening, Joining, and Connecting,” covers every conceivable type of mechanical fastener. When disassembly is not required, or when maximum strength is needed, then the only solution is a welded connection. All aspects of a welded connection are presented. Many connections must prevent leakage or provide cushioning, so a discussion of seals and their effect on a bolted connection is provided. The mating of parts without prior preassembly can be an important design requirement; therefore, this is where a detailed discussion of fits and tolerances is included.

Part 7, “Load Capability Considerations,” provides the designer with the rules for determining if a particular part will fail. This determination does not have to be a precise calculation, either under static or dynamic conditions, whether the part is acting as a beam or column, but to ignore these fundamental principles is to invite

disaster. This section seemed like the best place to discuss vibration and, just as important, its control.

Part 8, “Performance of Engineering Materials,” brings to bear the science of material behavior, to include the changes that take place during the manufacturing process. Once in service, machine elements are subject to constant wear and the adverse effects of corrosion.

Lastly, Part 9, “Classical Stress and Deformation Analysis,” provides the design engineer with the fundamental formulas for stress, deflection, and deformation, and includes special geometries such as curved elements and special loadings, which are found in cylinders under internal pressure when parts are press fitted.

One of the chapters included in the First and Second Editions, “Sections and Shapes—Tabular Data,” has been provided in this Third Edition as an appendix.

It is hoped that this Third Edition provides a dependable source of relevant information on the topics needed for the successful evolution of your design. Suggestions for improvement are welcome and will be appreciated.

*Thomas H. Brown, Jr.*

---

# PREFACE TO FIRST EDITION

---

There is no lack of good textbooks dealing with the subject of machine design. These books are directed primarily to the engineering student. Because of this, they contain much theoretical material that is amenable to mathematical analysis. Such topics are preferred by the instructor as well as the student because they appeal to the student's scientific, mathematical, and computer backgrounds; are well-defined topics with a beginning, a middle, and an end; and are easy to use in testing the student's knowledge acquisition. The limited amount of time available for academic studies severely limits the number of topics that can be used as well as their treatment. Since textbooks devoted to mechanical design inevitably reflect this bias, there is great need for a handbook that treats the universe of machine design—not just the readily teachable part.

The beginning designer quickly learns that there is a great deal more to successful design than is presented in textbooks or taught in technical schools or colleges. This handbook connects formal education and the practice of design engineering by including the general knowledge required by every machine designer.

Much of the practicing designer's daily informational needs are satisfied by various pamphlets or brochures, such as those published by the various standards organizations. Other sources include research papers, design magazines, and the various corporate publications concerned with specific products. More often than not, however, a visit to the design library or to the file cabinet will reveal that a specific publication is on loan, lost, or out of date. This handbook is intended to serve such needs quickly and immediately by giving the designer authoritative, up-to-date, understandable, and informative answers to the hundreds of such questions that arise every day in his or her work. Mathematical and statistical formulas and tabulations are available in every design office and, for this reason, are not included in this handbook.

This handbook has been written for working designers, and its place is on the designer's desk—not on the bookshelf. It contains a great many formulas, tables, charts, and graphs, many in condensed form. These are intended to give quick answers to the many questions that seem constantly to arise.

The introduction of new materials, new processes, and new analytical tools and approaches changes the way we design machines. Higher speeds, greater efficiencies, compactness, and safer, lighter-weight, and predictably reliable machines can result if designers keep themselves up to date on technological changes. This book presents machine design as it is practiced today; it is intended to keep the user in touch with the latest aspects of design.

Computer-aided design methods and a host of other machine-computation capabilities of tremendous value to designers have multiplied in the last few years. These have made large and lasting changes in the way we design. This book has been planned and written to make it easy to take advantage of machine-computation facilities of whatever kind may be available. Future developments in computer hardware and software will not render the content of this book obsolete.

This Handbook consists of the writings of 42 different contributors, all well-known experts in their field. We have tried to assemble and to organize the 47 chapters so as to form a unified approach to machine design instead of a collection of unrelated discourses. This has been done by attempting to preserve the same level of mathematical sophistication throughout and by using the same notation wherever possible.

The ultimate responsibility for design decisions rests with the engineer in charge of the design project. Only he or she can judge if the conditions surrounding the application are congruent with the conditions which formed the bases of the presentations in this Handbook, in references, or in any other literature source. In view of the large number of considerations that enter into any design, it is impossible for the editors of this Handbook to assume any responsibility for the manner in which the material presented here is used in design.

We wish to thank all contributors, domestic and foreign, for their patience and understanding in permitting us to fine-tune their manuscripts and for meeting and tolerating our exacting demands. We are also grateful to the many manufacturers who so generously provided us with advice, literature, and photographs. Most of the artwork was competently prepared and supervised by Mr. Gary Roys of Madrid, Iowa, to whom the editors are indebted.

Care has been exercised to avoid error. The editors will appreciate being informed of errors discovered, so that they may be eliminated in subsequent printings.

*Joseph E. Shigley  
Charles R. Mischke*

---

# ACKNOWLEDGMENTS

---

My enduring love and appreciation goes to my wife, Miriam, who has always encouraged me in my many endeavors throughout our marriage. Whether it is the day to day support in our life together, or in my annual quest for perfection in the State Fair amateur wine competition (a Blue Ribbon in 2003), or the hope of someday having a trophy deer hanging in the den, she has been steadfast in her strength and devotion. During the many months of my preoccupation with completing this project, she has been so wonderful and understanding.

I am grateful for the love of my three children, Sianna, Hunter, and Elliott, who have been so very patient through the many weekends without their Dad, and who are a continual joy to me. To my dear friend, Dr. Carl Zorowski, Professor Emeritus of Mechanical Engineering at NC State University, without whose weekly guidance over lunch for more than a decade, my insights in mechanical engineering and the machine design process would be sorely lacking. And to my new friends, and editors, Ken McCombs and Carol Levine, who have inspired me to produce the best I can produce, and in the process given me great honor to be a part of the McGraw-Hill family.

*Thomas H. Brown, Jr.*

## ABOUT THE EDITORS

---

**Joseph E. Shigley** (deceased) was awarded the B.S.M.E. and B.S.E.E. degrees from Purdue University, and an M.S. from the University of Michigan. He was Professor Emeritus at the University of Michigan, Fellow in the American Society of Mechanical Engineers, and received the Worcester Reed Warner medal in 1977 and their Machine Design Award in 1985. He was the author of eight books, including *Theory of Machines and Mechanisms* (with John J. Uicker, Jr.), and *Applied Mechanics of Materials*. Shigley began *Machine Design* as sole author in 1956, and it evolved into *Mechanical Engineering Design*. He was Coeditor-in-Chief of the *Standard Handbook of Machine Design* setting the model for such textbooks.

**Charles R. Mischke, Ph.D.**, is Professor Emeritus of Mechanical Engineering, Iowa State University, Ames, Iowa. He has authored many technical papers on designing to a reliability specification, computer-aided design, and design morphology. His was Coeditor-in-Chief, with J.E. Shigley, of the *Standard Handbook of Machine Design*, Second Edition, 1996.

**Thomas H. Brown, Jr., Ph.D., PE**, is a Faculty Associate at North Carolina State University. He currently manages both the FE review program and the Civil Engineering PE Review Program at the University's Institute for Transportation Research and Education (ITRE). In addition to fulfilling his course development and teaching responsibilities, Dr. Brown also teaches review courses for the Mechanical Engineering PE Review Program offered by the university and a private professional development firm. Prior to coming to NC State, Dr. Brown worked as a mechanical engineer for Scientific-Atlanta, Inc., Fluor Daniel Construction, and Burlington Industries, where he specialized in product development and machine design.