STANDARD HANDBOOK OF MACHINE DESIGN

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To the late Joseph Edward Shigley

Joseph Edward Shigley was awarded bachelor degrees in electrical (1931) and mechanical (1932) engineering by Purdue University, and a master of science in engineering mechanics (1946) by The University of Michigan. His career in engineering education began at Clemson College (1936–1956) and continued at The University of Michigan (1956–1978). Upon retirement, he was named Professor Emeritus of Mechanical Engineering by the Regents in recognition of his outstanding achievement and dedicated service.

At the time when Professor Shigley began thinking about his first book on machine design, many designers were unschooled, and textbooks tended to give results with only a brief explanation—they did not offer the reader many tools with which to proceed in other or new directions. Professor Shigley's first book, *Machine Design* (1956), showed his attention to learning and understanding. That milestone book is currently in its fifth edition. Other books followed, among which are *Theory of Machines and Mechanisms* (with John J. Uicker, Jr.), *Mechanical Engineering Design* (with Charles R. Mischke), and *Applied Mechanics of Materials.*

Early in the 1980s, Professor Shigley called Professor Mischke and said, "I've never done a Handbook before; there is no precedent in machine design, and it is time there was one. I propose we do it together. Take a couple of months to consider what ought to be in it, the organization and presentation style. Then we can get together and compare notes."

The result was the first edition of the *Standard Handbook of Machine Design* (1986), which won the Association of American Publishers Award for the best book in engineering and technology published in 1986. Eight *Mechanical Designers Workbooks* followed.

Professor Shigley received recognitions such as the grade of Fellow in the American Society of Mechanical Engineers, from which he also received the Mechanisms Committee Award in 1974, the Worcester Reed Warner Medal in 1977, and the Machine Design Award in 1985. I believe he would have given up all the above rather than give up the effect he had as mentor and tutor to students, and in guiding boys toward manhood as a scoutmaster.

He indeed made a difference.

Charles R. Mischke

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PREFACE TO THE 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

PREFACE TO THE SECOND EDITION

The introduction of new materials, new processes, and new (or more refined) analytical tools and approaches changes the way in which machines are designed. Complementary to the urge to update and improve, it is useful to look back in order to retain a perspective and appreciate how all this fits into the fabric of machine design methodology. Many of the machine elements we know today were known to the ancients. We have the advantage of improved materials, better manufacturing methods, and finer geometric control, as well as insightful theory and the opportunity to stand on the shoulders of the giants among our predecessors.

Assuring the integrity of a contemplated design, its components, and the aggregate machine or mechanism has always been a problem for the engineer. The methods of record include the following:

- *The Roman method* This method, developed in the Macedonia-Roman period, was to replicate a proven, durable design (with some peripheral improvements). Encyclopedic "books" were compiled for the guidance of designers. In strength-limited designs, the essential thought was, "Don't lean on your element any harder than was done in the durable, extant designs of the past." There are times when contemporary engineers still employ this method.
- *The factor of safety method (of Philon of Byzantium)* In today's terms, one might express this idea as

  $$n = \frac{\text{loss-of-function load}}{\text{impressed load}} = \frac{\text{strength}}{\text{stress}}$$

  for linear load-stress relations. Alternatively,

  $$\text{Allowable load} = \frac{\text{loss-of-function load}}{n}$$

  or

  $$\text{Allowable stress} = \frac{\text{strength}}{n}$$

  for linear load-stress relations. The factor of safety or design factor was experiential and came to consider uncertainty in load as well as in strength.
- *The permissible stress method* Since the concept of stress was introduced by Cauchy in 1822, some engineers have used the idea of permissible stress with load uncertainty considered, and later with the relevant material strength included, as for example in

  $$0.40S_y \le (\sigma_{\text{all}})_{\text{bending}} \le 0.60S_y$$

It is not clear whether the material strength uncertainty is included or not. When the word "allowable" or "permissible" is used among engineers, it is important to clearly define what is, and what is not, included.

- *Allowable stress by design factor* The definition of allowable stress σ_{all} is expressed as

$$\sigma_{\text{all}} = \frac{\text{strength}}{n_d^m}$$

where $\sigma = \phi P^m$, i.e., stress is proportional to the mth power of load P. The design factor n_d is experiential and includes load and material strength uncertainty. In gear and cam design, contact stresses are not linear with load. In the form above, if the design factor is 2, then doubling the load creates the loss-of-function load, *whether the stress is bending or hertzian.*

- *Stochastic design factor method* Recognizing that strength **S**, load-induced stress $\boldsymbol{\sigma}$, and the design factor $\mathbf{n}_d$ are stochastic (random) variables, one writes $\mathbf{n}_d = \mathbf{S}/\boldsymbol{\sigma}$. For lognormal strength and lognormal loading, the mean design factor $\bar{n}_d$ is

$$\bar{n}_d = \exp[C_n(z - C_n/2)]$$

where

$$C_n = \sqrt{C_S^2 + C_\sigma^2} = \sqrt{C_S^2 + C_P^2}$$

in which the C's are coefficients of variation of strength, stress, load, or design factor as subscripted. From this point on,

$$\bar{\sigma}_{\text{all}} = \frac{\bar{S}}{\bar{n}_d}$$

and one proceeds deterministically using mean values. Note in particular that $\bar{n}_d$ is *quantitatively* experiential from data.

- *The stochastic method* The design factor n_d and the factor n are not used. Distributions are identified, and by simulation procedures the reliability corresponding to a decision set is identified. The computer becomes an important tool.

The practicing designer should be familiar with all of these methods. Although some of them may not be the method of choice under particular circumstances, it is important to understand them all in order to communicate with others and to follow their work.

Developments since the appearance of the first edition of this book in 1986 are reflected in additions to chapters, rewritten chapters, and completely new chapters. More attention is being paid to probabilistic approaches to the design of machinery, and information and methods continue to develop. The reader can appreciate where parts fit in with the historical summary above.

Chapter 2, "Statistical Considerations," has been rewritten to show the relationship between the design factor method and the stochastic methods of design as the inevitable uncertainties are considered. The result on the necessary size of the mean design factor of the interfering of a normal stress with a normal strength is shown. The more useful result on the necessary size of the mean design factor of the interference of a lognormal stress with a lognormal strength is explained. General interference methodology is included, as well as a caution on the nature of numbers, with the reason why significant numbers are rarely useful and possibly harmful.

Chapter 5, "Computer Considerations," has had material added on the important application of computer simulation and, very importantly, on assessing the confidence interval on the result.

Chapter 8, "The Strength of Cold-Worked and Heat-Treated Steels," now includes a Fortran code for cold-work property predictions using the method of Datsko.

Chapter 13, "Strength under Dynamic Conditions," now includes both stochastic and deterministic Marin fatigue reduction factors, and the correlation method for estimating endurance limits in steels. A tabular summary of fatigue equations is also presented in Customary Engineering Units and in SI. The methods for estimating the strength amplitude component and its coefficient of variation are shown for distortion energy–Gerber, ASME-elliptic, and Smith-Dolan fatigue loci. A section on complicated stress variation patterns has also been added.

Chapter 37, "Shafts," has been completely rewritten to show the interplay between deflections (including shear deflections in short shafts) and stress-strength considerations. The fatigue failure loci featured are those that cannot be statistically rejected. These are the distortion energy–Gerber and the ASME-elliptic loci. A section on estimating the first critical speed using Rayleigh's equation has been added.

A new Chapter 9, "Usability," has been added, recognizing that human capabilities and limitations are an integral part of designing tools and machines, and that a practicing machine designer has need for a handy reference. The four essential steps to assure that the product or system fits the operator are enumerated, and sources of available anthropometric information are given. Some basic information is included and references identified.

A new Chapter 10, "Safety," has been added. The ASME Code of Ethics states, "Engineers shall hold paramount the safety, health and welfare of the public in the performance of their professional duties." This chapter identifies the why of safety; what safety is; the nature of hazard, risk, and danger; and the designer's obligation. Human beings interact with all products in the processes of designing, manufacturing, and maintaining them. This ties in with Chaps. 1 and 9.

A new Chapter 11, "Minimizing Engineering Effort," addresses a topic that engineers are reluctant to discuss, namely, "How do you know you are right?" Intertwined with this is the matter of checking and its effectiveness.

The chapter "Gaskets and Seals" has been partitioned into "Gaskets" and "Seals" for this edition. New contributors present the first edition topics of "Power Screws" and "Chain Drives." As in the previous edition, the Handbook continues to be written to take easy advantage of whatever kind of machine-computation facilities may be available. Future developments in hardware and software will not render the contents of this book obsolete.

This edition contains the work of 41 different contributors, all well-known experts in their fields. There are now 50 chapters, assembled and organized to form a coherent approach to machine design.

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 applications are congruent with the circumstances 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 conditions 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.

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Joseph E. Shigley
Charles R. Mischke

ABOUT THE EDITORS

Joseph Edward Shigley is Late Professor Emeritus of Mechanical Engineering, The University of Michigan. Refer to the Dedication (p. iii).

Charles R. Mischke, Professor Emeritus of Mechanical Engineering, Iowa State University, B.S.M.E. (1947), M.M.E. (1950) Cornell University, Ph.D. (1953) University of Wisconsin. He served on the faculty of mechanical engineering, University of Kansas (1953–1957), as Professor and Chairman of Mechanical Engineering, Pratt Institute (1957–1964), and as Professor of Mechanical Engineering at Iowa State University (1964–1992). His books include *Elements of Mechanical Analysis* (1963), *Introduction to Computer-Aided Design* (1968), and *Introduction to Engineering through Mathematical Model Building* (1980), and he was Coeditor-in-Chief, with J. E. Shigley, of the *Standard Handbook of Machine Design* (1986) and *Mechanical Designers' Workbooks,* eight volumes (1989). He coauthored with J. E. Shigley *Mechanical Engineering Design,* 5th ed. (1989).

He had authored many technical papers on designing to a reliability specification, computer-aided design, and design morphology. He created the CADET (*C*omputer-*A*ugmented *D*esign *E*ngineering *T*echnique) software, and he served on the Reliability, Stress Analysis and Failure Prevention Committee of the American Society of Mechanical Engineers (Reliability Subcommittee chair).

Dr. Mischke's honors and awards include Life Fellow, A.S.M.E. (1993), Centennial Certificate of Recognition of A.S.E.E. (1993), the Ralph Coats Roe Award of A.S.E.E. (1991), The Iowa Legislature Teaching Excellence Award (1991), the Machine Design Award of A.S.M.E. (1990), the Association of American Publishers Award (1987), Outstanding Teaching Award, Iowa State University (1980), the Ralph Teeter Award of the Society of Automotive Engineers (1977), and Alcoa Foundation Professor (1974).