
Peter R.N. Childs
MECHANICAL
DESIGN
ENGINEERING
HANDBOOK
B
H

Mechanical Design Engineering Handbook

Peter R.N. Childs

ELSEVIER

AMSTERDAM • BOSTON • HEIDELBERG • LONDON • NEW YORK • OXFORD
PARIS • SAN DIEGO • SAN FRANCISCO • SINGAPORE • SYDNEY • TOKYO

Butterworth-Heinemann is an imprint of Elsevier

Butterworth-Heinemann is an imprint of Elsevier
The Boulevard, Langford Lane, Kidlington, Oxford, OX5 1GB, UK
225 Wyman Street, Waltham, MA 02451, USA

First published 2014

Notice
Knowledge and best practice in this field are constantly changing. As new research and experience broaden our understanding, changes in research methods, professional practices, or medical treatment may become necessary.

Practitioners and researchers must always rely on their own experience and knowledge in evaluating and using any information, methods, compounds, or experiments described herein. In using such information or methods they should be mindful of their own safety and the safety of others, including parties for whom they have a professional responsibility.

To the fullest extent of the law, neither the Publisher nor the authors, contributors, or editors, assume any liability for any injury and/or damage to persons or property as a matter of products liability, negligence or otherwise, or from any use or operation of any methods, products, instructions, or ideas contained in the material herein.

British Library Cataloguing in Publication Data
A catalogue record for this book is available from the British Library

Library of Congress Cataloguing in Publication Data
A catalog record for this book is available from the Library of Congress

ISBN: 978-0-08-097759-1

Mechanical Design Engineering Handbook

Preface

The prior knowledge base in design and engineering, as with nearly all domains, is extensive. We have been designing and producing a wide range of sophisticated machines and systems for centuries. The detailed design of many machine elements and types of machinery has been codified and significant expertise is readily available. Just knowing that someone else has successfully produced a product or system can act as inspiration or provide direction for a similar product or the design of a subsystem that uses associated technology, or needs to have comparable functions.

Many attempts have been made at defining design. The word can be used as a verb or noun, describing the process and the outcome of design, respectively. Referring to design as a process, it can be considered to include all the activities of market assessment and user requirements, specification, concept generation and idea development, embodiment of details, risk mitigation, consideration of manufacture and production, and implementation. Referring to design as a noun, the term is commonly used to describe an artifact such as a vehicle, item of fashion or other product, with the associated features and merits. This may include description or commentary on aesthetic, ergonomic, and technical features. In this book, an inclusive approach to design is used with consideration of a range of functionalities ranging from technical, aesthetic, social, economic, and latent. Design is considered to be the process of conceiving, developing, and realizing products, artifacts, processes, systems, services, and experiences with the aim of fulfilling identified or perceived needs or desires typically working within defined or negotiated constraints.

Engineering involves significant overlap with design and, indeed, it is often difficult to make a clear distinction. A common distinction is the use of quantitative analysis in engineering to aid and inform the development, simulation, testing, and refinement of a system or product. Engineering can thus be considered to be the application of scientific and mathematic principles in combination with professional and domain knowledge, in order to design, develop, and deliver artifacts, products, and systems to realize a societal, commercial, or organization requirement or opportunity. Mechanical engineering refers to the use of engineering processes to applications of a mechanical nature, typically involving moving components or energy processes. Mechanical engineering heavily relies on the engineering sciences of thermodynamics and mechanics, often integrated through design, in the

development and refinement of a solution for a specific requirement. The title for this book comes from the blend of mechanical and design engineering, the latter with its heritage in the on-going collaborations between Imperial College London and the Royal College of Art through the Innovation Design Engineering double masters, of which I have the honor of being joint course director.

The detailed design of a wide range of machine elements that are commonly used in mechanisms and machines has been the focus of attention of many companies and research groups around the world. Examples of such machine elements include bearings, shafts, gears, belts, chains, clutches, brakes, seals, and springs. Many of these are available as stock items or standardized components that are produced by a range of companies, enabling the engineer or designer to focus attention on selection of appropriate stock items and the integration of these within the application of interest, rather than having to repeat the development of previous knowledge. For other machine elements such as shafts, some clutches and brakes, and seals, their design can take advantage of prior knowledge and design guidelines.

Industry is typically concerned with the development of return for investors, or owners, within their specific product or service sector. A wide range of approaches is employed to manage the development and delivery process for new products and systems, or the manufacture and production, and delivery, of artifacts and services. Many models and approaches for the design process are employed in industry and area often bespoke to the particular organization concerned. Studies across a range of industries have identified some commonality in approach and a number of models have been proposed as representative of a standardized approach to design, and the management of design. A selection of these is presented in Chapter 1, providing an overview of typical approaches to the design process and its management.

The objective or quantitative definition of the attributes and requirements for a product, artifact, or system, represents a common activity in design and engineering. This enables an assessment of what the design is required to deliver and is often used to monitor the success of a design proposal and in contractual agreements. Two common approaches to specification are introduced in Chapter 2, including the use of product design specification pro-forma tables and quality functional deployment.

Whether the engineering or design activity involves integration of existing machine elements within a mechanism, or the design of original features and components, in the design of a brand new product or system, ideas are important. The development of ideas and the use of a range of creativity tools are introduced in Chapter 3.

An overview of the variety of machine elements is introduced in Chapter 4. The design and selection of plain surface bearings and rolling element bearings are considered in

Chapters 5 and 6. Chapter 5 includes an introduction to the wide range of bearing types and presents a selection method for boundary lubricated bearings, as well as a modeling approach for full-film hydrodynamic bearings that can be used to assess the suitability of an initial design proposal. The selection of rolling element bearings based on the classical bearing life equation is introduced in Chapter 6 along with a brief consideration of bearing arrangements. Shafts are considered in Chapter 7 with a particular focus on sizing a shaft to limit deflection to adequate limits and assessing dynamic characteristics.

Gears, critical for transforming speed and torque in transmission systems, are introduced in Chapters 8–11. Chapter 8 provides an overview of a wide range of types of gears and also presents an initial selection procedure for spur gears based on the Lewis formula for bending. The introduction of more comprehensive analysis methods using the American Gear Manufacturer Association (AGMA) equations for bending and contact stress for spur and helical gears, bevel, and worm and wheel gears, is presented in Chapters 9, 10, and 11, respectively. The related transmission elements of belts and chains are introduced in Chapter 12, with a particular focus on the selection of belts and chains from stock suppliers using standard selection procedures. Clutches and brakes are introduced in Chapter 13. This chapter includes simple design procedures for single and multiple disk clutches, long- and short-shoe drum brakes, and calliper disk brakes.

Seals are used in a wide range of machinery to prevent or limit the flow of fluids between regions in a machine and to exclude dirt or contaminants. Chapter 14 provides an overview of the wide range of types of seals and also gives guidance for the sizing of O rings for static and dynamic applications using data from British Standards, as well as modeling methods for assessing the leakage of labyrinth and bush seals.

Springs are manufactured by a wide range of world-wide manufacturers and available as both stock items or bespoke designs. Chapter 15 introduces the design of a wide range of types of springs, including helical compression, helical extension, helical torsion, leaf, and Belleville springs.

A wide range of fastening technologies is available for permanent and semipermanent joining of components. A range of these including threaded fasteners and rivets is introduced in Chapter 16, along with a brief consideration of adhesives, welding, and snap fasteners. The selection of wire rope is briefly introduced in Chapter 17. Pneumatic and hydraulic components, the majority available as stock items, are introduced in Chapter 18.

Although a component, or process, may have a designated nominal dimension or performance measure, the actual dimension or performance will likely vary within limits of this value. Chapter 19 introduces the subject of tolerance with particular consideration of component tolerances for the assembly of cylindrical components, a brief consideration of geometric tolerances, and an introduction to statistical tolerance approaches.

The majority of material presented in this book represents a classic approach to the design and selection of machine elements. A cook-book recipe approach has been adopted for many of these, enabling the rapid development of a proposal for the machine element concerned and its evaluation. It is important to acknowledge the limitations of such an approach as the configuration, or selection, may be far from optimal. A typical approach to mitigate against nonoptimal selections is to explore additional selections with variation of a parameter, say a size above and below, or a slightly stronger and weaker material, to see if the outcome is favorable and then follow this lead. In addition, a keen eye on fundamental physics and engineering principles is necessary in the development of any solution or design proposal.

A considerable quantity of the material in this book has arisen from two editions of my earlier book, *Mechanical Design*. This new handbook incorporates extensions to the treatment of former chapters on bearings, gears, belts and chains, clutches and brakes, seals, springs, fasteners, and tolerance. Specifically for this handbook, new chapters on design, specification, ideation, bevel gears, worm and wheel gears, wire rope, and pneumatics and hydraulics have been developed.

The aims of this book are thus to present an overview of the design process and to introduce the technology and selection of a number of specific machine elements that are fundamental to a wide range of mechanical engineering design applications. I hope it is useful to you.

Peter R.N. Childs

– July 2013

Acknowledgments

Many colleagues, associates in industry and engineering institutions, and students have helped me throughout my career and in the forming of the material presented in this book. I am particularly indebted to my former colleagues at the University of Sussex, and my current colleagues at Imperial College London and the Royal College of Art, who have consistently commented on and enabled refinement of notes, designs, and methodologies. I have significantly benefited over the years from membership of both the Institution of Mechanical Engineers (IMechE) and the American Society of Mechanical Engineers, in particular through the IMechE's Automobile Southern Centre and the Southern Region, and also the International Gas Turbine Institute.

I would also like to acknowledge my indebtedness to the wide number of companies and organizations who have sponsored research or development contracts with me over the years, enabling the development of invaluable experience, including Rolls-Royce plc, Alstom, Snecma, DaimlerChrysler, MTU, Volvo, Johnson Matthey, Siemens, Industriales Turbinas Propulsores, Fiat Avio, Airbus, Ricardo Consulting Engineers, Ford, Rio Tinto, the EPSRC, Technology Strategy Board and the EU, as well and many small and medium enterprises. I have also been fortunate to be able to form a number of companies over the years, with a wide range of accompanying experiences and interactions that all help to provide a richer basis from which to develop the material presented here.

Students, and novice engineers and designers, have played a huge role in my professional career. I am indebted to them all for the diverse experiences, and challenges to material, examples, and notes, as well as endorsements.

Thank you to the various authors and publishers who have granted permission to reproduce or adapt images and material. In particular, I would like to acknowledge Audi, the Design Council, Chapman and Hall, J.C. Bamford, Wiley, Pearson, Fiskars, John Crane, SKF, Rolls-Royce plc, Cross and Morse, NASA, McGraw Hill, Grainger, the American Gear Manufacturers Association, British Standards, Fenner Drives, Renold Chain, IHS-ESDU, Associated Spring, Noble & Son Ltd, AISI, Wire Rope Technical Board, and Ford.

I would also like to thank Sol Lee and Ashley Hall for their parts in the first image in the book. Thank you to Dr Marco Aurisicchio for his contributions toward Chapter 2. The staff at Arnold, Butterworth Heinemann, and Elsevier have been professional and encouraging throughout the production of the two editions of *Mechanical Design* and this new handbook. Finally, thank you to my family, and in particular my wife Jo, for accommodating the hours of writing, drawing, and distraction associated with producing any book.

About the Author

Peter R.N. Childs is the Professorial Lead in Engineering Design at Imperial College London. His general interests include: fluid flow and heat transfer, particularly rotating flow and flow system design for gas turbine engine applications; creativity tools and innovation; mechanical design, machine elements, and detailed design; sustainable energy component, concept, and system design. Prior to his current post at Imperial, he was director of the Rolls-Royce supported University Technology Centre for Aero-Thermal Systems, director of InQbate, and professor at the University of Sussex.

He has contributed to over 140 refereed journal and conference papers since completion of his doctorate in 1991, and several books including monographs on rotating flow (Elsevier and ESDU (Engineering Sciences Data Unit)), labyrinth seals (ESDU) and temperature measurement (Elsevier and ESDU), and a text book on mechanical design (Butterworth Heinemann). He has been involved in research and development contracts for Rolls-Royce plc, Alstom, Snecma, DaimlerChrysler, MTU, Volvo, Johnson Matthey, Siemens, Industriales Turbinas Propulsores, Fiat Avio, Airbus, Ricardo Consulting Engineers, Ford, Rio Tinto, the EPSRC, TSB and the EU, as well as a number of SMEs (small and medium enterprises).

He has been the Chairman of the South Eastern Region of the Institution of Mechanical Engineers. He has won the American Society of Mechanical Engineers (ASME) – International Gas Turbine Institute John P. Davis award for exceptional contribution to the literature of gas turbine technology and Institution of Mechanical Engineers and American Society of Mechanical Engineers best paper awards. He is a Fellow of the American Society of Mechanical Engineers, a Fellow of the Institution of Mechanical Engineering, and a Fellow of the Royal Society for the Arts and Manufactures. He is a member of the European Turbomachinery Network, an active member of the ASME K14 Heat Transfer Committee, and has been a Vanguard Chair for the ASME Turbo Expo, as well as a regular session chair. His role at Imperial includes being the joint course director for the Innovation Design Engineering degree with the Royal College of Art, leading the Design Engineering Group, CTO of QBot Ltd, Design lead for the Manufacturing Futures Lab, and a member of the educational executive for the Climate Knowledge Innovation Centre. He is also the Creative Director for Iceni Labs.

Contents