

# MACHINE DESIGNERS REFERENCE



**Jennifer Marrs, P.E.**

**Industrial Press, Inc.  
New York**

## **J. Marrs, P.E.**

## **Library of Congress Cataloging-in-Publication Data**

Marrs, Jen.

Machine designers reference / Jen Marrs.

p. cm.

Includes bibliographical references and index.

ISBN 978-0-8311-3443-3 (hard cover)

1. Machine design—Handbooks, manuals, etc.

2. Mechanical engineering—Handbooks, manuals, etc. I. Title.

TJ230.M37 2011

621.8'15—dc23

2011030875

### **Industrial Press, Inc.**

989 Avenue of the Americas

New York, NY10018

Sponsoring Editor: John Carleo

Interior Text and Cover Design: Janet Romano

Developmental Editor: Robert Weinstein

Copyright © 2012 by Industrial Press Inc., New York. Printed in the United States of America. All rights reserved. This book, or any parts thereof, may not be reproduced, stored in a retrieval system, or transmitted in any form without the permission of the publisher.

SOLIDWORKS is a registered trademark of Dassault Systèmes SolidWorks Corporation

Information contained in this work has been obtained by Industrial Press Inc. from sources believed to be reliable. However, neither Industrial Press nor its authors guarantee the accuracy or completeness of any information published herein and neither Industrial Press nor its authors shall be responsible for any errors, omissions, or damages arising out of the use of this information. This work is published with the understanding that Industrial Press 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.

Many pieces of art have been redrawn by Lineworks, Inc.

Composition was created by Lapiz Digital

10 9 8 7 6 5 4 3 2 1

## BRIEF TABLE OF CONTENTS

<b>About the Authors .....</b>	<b>xiii</b>
<b>Acknowledgments .....</b>	<b>xv</b>
<b>Introduction .....</b>	<b>xvii</b>
<b>Chapter 1: Design and Analysis .....</b>	<b>01</b>
1.1: Design of Machinery .....	03
1.2: Engineering Units. ....	15
1.3: Equations .....	18
<b>Chapter 2: Ergonomics and Machine Safety (Co-written with E. Smith Reed, P.E.) .....</b>	<b>35</b>
2.1: Ergonomics. ....	38
2.2: Machine Safety: Design Process. ....	47
2.3: Machine Safeguarding .....	51
2.4: Other Safety Issues. ....	65
2.5: Recommended Resources .....	71
<b>Chapter 3: Dimensions and Tolerances .....</b>	<b>93</b>
3.1: Limits, Fits, and Tolerance Grades .....	95
3.2: Tolerances on Drawings, and GD&T .....	116
3.3: Tolerance Stack-Ups (Written by Charles Gillis, P.E.)....	127
<b>Chapter 4: Precision Locating Techniques (Written by Charles Gillis, P.E.) .....</b>	<b>179</b>
<b>Chapter 5: Pins, Keys, and Retaining Rings .....</b>	<b>215</b>

**iv Brief Table of Contents**

<b>Chapter 6: Pipe Threads, Threaded Fasteners, and Washers .....</b>	<b>279</b>
6.1: Pipe and Port Threads .....	281
6.2: Threaded Fasteners and Washers.....	285
<b>Chapter 7: Welds and Weldments .....</b>	<b>357</b>
<b>Chapter 8: Materials, Surfaces, and Treatments .....</b>	<b>369</b>
8.1: Materials.....	371
8.2: Surface Finish.....	391
8.3: Heat Treatment.....	398
8.4: Surface Treatment .....	407
<b>Chapter 9: Force Generators.....</b>	<b>413</b>
9.1: Springs .....	415
9.2: Pneumatics .....	466
9.3: Electric Motors.....	482
<b>Chapter 10: Bearings .....</b>	<b>501</b>
10.1: Plain Bearings .....	503
10.2: Rolling Element Bearings .....	510
10.3: Linear Bearings .....	534
<b>Chapter 11: Power Transmission Devices .....</b>	<b>543</b>
11.1: Shafts .....	547
11.2: Shaft Couplings .....	563
11.3: Gears (Written by Gregory Aviza) .....	574
11.4: Gearboxes.....	614
11.5: Belts and Chains.....	627
11.5.1: Belts .....	629
11.5.2: Chains .....	655
11.6: Lead, Ball, and Roller Screws .....	664
<b>Chapter 12: Machine Reliability and Performance .....</b>	<b>681</b>

## COMPLETE TABLE OF CONTENTS

<b>1.</b>	<b>Design and Analysis . . . . .</b>	<b>01</b>
<b>  1.1.</b>	<b>Design of Machinery . . . . .</b>	<b>03</b>
•	Recommended Resources. . . . .	03
•	Functional Design Specification . . . . .	03
•	Research . . . . .	08
•	Synthesis and Conceptual Design . . . . .	09
•	Detail Design and Analysis . . . . .	10
•	Factors of Safety. . . . .	13
•	Critical Considerations: Design of Machinery . . . . .	14
•	Best Practices: Design of Machinery . . . . .	14-15
<b>  1.2.</b>	<b>Engineering Units . . . . .</b>	<b>15</b>
•	Recommended Resources. . . . .	15
•	Engineering Units. . . . .	15
•	Unit Conversions . . . . .	17
<b>  1.3.</b>	<b>Equations . . . . .</b>	<b>18</b>
•	Recommended Resources. . . . .	18
•	Tables of Equations . . . . .	18-33
<b>2.</b>	<b>Ergonomics and Machine Safety. . . . .</b>	<b>35</b>
<b>  2.1.</b>	<b>Ergonomics . . . . .</b>	<b>38</b>
•	Recommended Resources. . . . .	39
•	Body and Workspace Dimensions . . . . .	39
•	Body Dimensions . . . . .	39
•	Workspace, Clearances, Enclosures, and Access Openings . . . . .	39
•	Operator Physical Capabilities and Limitations: Reaching / Grasping / Moving / Lifting. . . . .	41
•	Critical Considerations: Ergonomics . . . . .	46
<b>  2.2.</b>	<b>Machine Safety: Design Process . . . . .</b>	<b>47</b>
•	Recommended Resources. . . . .	48
•	Risk Assessment. . . . .	48
•	Risk Reduction . . . . .	50
•	Critical Considerations: Machine Safety: Design Process. . . . .	51
<b>  2.3.</b>	<b>Machine Safeguarding . . . . .</b>	<b>51</b>
•	Recommended Resources. . . . .	53
•	Guards. . . . .	53
•	Protective Devices . . . . .	58
•	Procedural Safeguarding: Information, Instructions and Warnings . . . . .	62
•	Warnings Included in the Manual . . . . .	63
•	Warning Labels Posted on the Machine . . . . .	64
•	Critical Considerations: Machine Safeguarding . . . . .	65

**vi Complete Table of Contents**

<b>2.4. Other Safety Issues .....</b>	<b>65</b>
• Recommended Resources.....	65
• Emission of Airborne Substances or Modification of Surrounding Atmosphere.....	66
• Emission of Radiation, Intense Light, Vibration, Heat .....	66
• Emission of Noise .....	66
• Hand / Arm Vibration .....	67
• Whole Body Vibration.....	67
• Machine Use in Explosive Atmospheres.....	68
• Moving the Machine .....	68
• Machine Stability .....	68
• Lubrication .....	69
• Danger Warning Alarm Signaling: Audible Signals and Visual Signals .....	69
• Lockout / Tagout Requirements.....	69
• Emergency Stop Devices .....	70
• Critical Considerations: Other Safety Issues .....	71
<b>2.5. Recommended Resources .....</b>	<b>71</b>
• Governmental Regulations, Statutes, Codes, and Publications .....	72
• Books .....	74
• Industry Safety Standards.....	76
• Internet Web Sites .....	84
• Application of Literature to Design Topics.....	85
<b>3. Dimensions and Tolerances.....</b>	<b>93</b>
<b>3.1. Limits, Fits, and Tolerance Grades .....</b>	<b>95</b>
• Recommended Resources.....	95
• Types of Fits and Their Limits.....	95
• Machining Tolerances .....	102
• Limits of Size Data.....	102
• Critical Considerations: Limits, Fits, and Tolerance Grades .....	116
• Best Practices: Limits, Fits, and Tolerance Grades .....	116
<b>3.2. Tolerances on Drawings, and GD&amp;T .....</b>	<b>116</b>
• Recommended Resources.....	116
• Implied Tolerances.....	117
• Geometric Dimensioning and Tolerancing (GD&T).....	117
• Critical Considerations: Tolerances on Drawings, and GD&T .....	126
• Best Practices: Tolerances on Drawings, and GD&T .....	127
<b>3.3. Tolerance Stack-Ups .....</b>	<b>127</b>
• Recommended Resources.....	128
• Design Practice.....	128
• The Tolerance Stack-Up Chain .....	129
• Preliminary Tolerance Assignment .....	133
• Analysis and Assignment Methods .....	134

• Practical Applications.....	146
• Summary.....	174
• Critical Considerations: Tolerance Stack-Ups .....	176
• Best Practices: Tolerance Stack-Ups .....	177
<b>4. Precision Locating Techniques .....</b>	<b>179</b>
• Recommended Resources.....	181
• Design Requirements .....	181
• The Two-Hole Problem .....	182
• Datum Reference Frame.....	185
• Design Process .....	187
• Precision Locating Techniques .....	191
• Critical Considerations: Precision Locating Techniques .....	212
• Best Practices: Precision Locating Techniques .....	212
<b>5. Pins, Keys, and Retaining Rings.....</b>	<b>215</b>
• Recommended Resources.....	217
• Pins and Keys in Shear.....	217
• Pins.....	219
• Keys .....	223
• Retaining Rings .....	225
• Critical Considerations: Pins, Keys, and Retaining Rings .....	226
• Best Practices: Pins, Keys, and Retaining Rings .....	227
• Component Data.....	227
<b>6. Pipe Threads, Threaded Fasteners and Washers.....</b>	<b>279</b>
<b>   6.1. Pipe and Port Threads .....</b>	<b>281</b>
• Recommended Resources.....	281
• Standards .....	281
• Critical Considerations: Pipe and Port Threads .....	282
• Best Practices: Pipe and Port Threads .....	282
• Pipe and Port Thread Dimensions .....	282
<b>   6.2. Threaded Fasteners and Washers.....</b>	<b>285</b>
• Recommended Resources.....	285
• Fastener Threads.....	286
• Tap Drills .....	288
• Fastener Types, Materials, and Selection.....	294
• Grades and Strength of Fasteners.....	295
• Torque of Fasteners .....	298
• Critical Considerations: Threaded Fasteners and Washers.....	298
• Best Practices: Threaded Fasteners and Washers.....	299
• Component Information .....	301
• Component Data.....	308

**viii** Complete Table of Contents

7. Welds and Weldments . . . . .	357
• Recommended Resources . . . . .	359
• Weld Types . . . . .	360
• Weld Symbols . . . . .	361
• Weldment Drawings . . . . .	364
• Materials and Treatments . . . . .	365
• Critical Considerations: Welds and Weldments . . . . .	367
• Best Practices: Welds and Weldments . . . . .	368
8. Materials, Surfaces, and Treatments . . . . .	369
8.1. Materials . . . . .	371
• Recommended Resources . . . . .	371
• Metals Nomenclature . . . . .	371
• Material Properties . . . . .	372
• Common Material Choices . . . . .	376
• Materials Data . . . . .	382
• Critical Considerations: Materials . . . . .	390
• Best Practices: Materials . . . . .	391
8.2. Surface Finish . . . . .	391
• Recommended Resources . . . . .	391
• Surface Finish Symbols . . . . .	392
• Surface Finish and Tolerance . . . . .	394
• Surface Finish Data . . . . .	395
• Critical Considerations: Surface Finish . . . . .	398
• Best Practices: Surface Finish . . . . .	398
8.3. Heat Treatment . . . . .	398
• Recommended Resources . . . . .	399
• Hardness . . . . .	399
• Heat Treatment Processes . . . . .	401
• Heat Treatment and Distortion . . . . .	403
• Hardness from Heat Treating . . . . .	403
• Critical Considerations: Heat Treatment . . . . .	406
• Best Practices: Heat Treatment . . . . .	407
8.4. Surface Treatment . . . . .	407
• Recommended Resources . . . . .	407
• Common Surface Treatment Types . . . . .	408
• Selection of Surface Treatments . . . . .	410
• Critical Considerations: Surface Treatment . . . . .	412
• Best Practices: Surface Treatment . . . . .	412

<b>9.</b>	<b>Force Generators . . . . .</b>	<b>413</b>
<b>9.1.</b>	<b>Springs . . . . .</b>	<b>415</b>
•	Recommended Resources . . . . .	415
•	Spring Types . . . . .	415
•	Spring Materials . . . . .	418
•	Helical Coil Spring Terminology . . . . .	422
•	Helical Coil Spring Fatigue . . . . .	423
•	Helical Coil Compression Springs . . . . .	426
•	Helical Compression Spring Catalog Selection Steps . . . . .	429
•	Helical Compression Spring Design Steps . . . . .	437
•	Helical Coil Extension Springs . . . . .	440
•	Helical Extension Spring Catalog Selection Steps . . . . .	443
•	Helical Extension Spring Design Steps . . . . .	447
•	Helical Coil Torsion Springs . . . . .	450
•	Helical Torsion Spring Catalog Selection Steps . . . . .	451
•	Helical Torsion Spring Design Steps . . . . .	454
•	Belleville Spring Washers . . . . .	456
•	Belleville Spring Washer Catalog Selection Steps . . . . .	459
•	Belleville Spring Washer Design Steps . . . . .	463
•	Critical Considerations: Springs . . . . .	465
•	Best Practices: Springs . . . . .	465
<b>9.2.</b>	<b>Pneumatics . . . . .</b>	<b>466</b>
•	Recommended Resources . . . . .	466
•	Pressure and Regulation . . . . .	467
•	Pneumatic Circuits . . . . .	467
•	Pneumatic Symbols . . . . .	468
•	Air Actuators . . . . .	468
•	Sizing Air Actuators . . . . .	472
•	Calculating $C_v$ . . . . .	474
•	Pneumatic Valves . . . . .	476
•	Sizing Valves . . . . .	480
•	Critical Considerations: Pneumatics . . . . .	480
•	Best Practices: Pneumatics . . . . .	481
<b>9.3.</b>	<b>Electric Motors . . . . .</b>	<b>482</b>
•	Recommended Resources . . . . .	482
•	Electrical Power . . . . .	482
•	Motor Terminology . . . . .	483
•	AC Motors . . . . .	484
•	DC Motors . . . . .	489
•	Electric Motor Controls . . . . .	490
•	Electric Motor Frames and Enclosures . . . . .	493
•	Electric Motor Sizing . . . . .	494
•	Critical Considerations: Electric Motors . . . . .	499
•	Best Practices: Electric Motors . . . . .	499

**x** Complete Table of Contents

<b>10.</b>	<b>Bearings.....</b>	501
<b>10.1. Plain Bearings .....</b>		503
<ul style="list-style-type: none"> <li>• Recommended Resources..... 503</li> <li>• Lubrication of Plain Bearings ..... 503</li> <li>• Bearing Materials for Boundary Lubrication..... 506</li> <li>• Boundary Lubricated Sleeve Bearings..... 506</li> <li>• Sleeve Bearing Selection Procedure for Boundary Lubrication ..... 509</li> <li>• Critical Considerations: Plain Bearings ..... 510</li> <li>• Best Practices: Plain Bearings..... 510</li> </ul>		
<b>10.2. Rolling Element Bearings .....</b>		510
<ul style="list-style-type: none"> <li>• Recommended Resources..... 511</li> <li>• Lubrication, Seals, and Shields ..... 511</li> <li>• Bearing Characteristics..... 512</li> <li>• Bearing Types..... 514</li> <li>• Radial Ball and Roller Bearing Dimensions and Tolerances ..... 520</li> <li>• Bearing Arrangements ..... 525</li> <li>• Loads on Bearings ..... 527</li> <li>• Bearing Load Ratings and Life Expectancy ..... 529</li> <li>• Bearing Selection Procedure for a Rotating Shaft Application..... 531</li> <li>• Critical Considerations: Rolling Element Bearings ..... 533</li> <li>• Best Practices: Rolling Element Bearings ..... 534</li> </ul>		
<b>10.3. Linear Bearings .....</b>		534
<ul style="list-style-type: none"> <li>• Recommended Resources..... 534</li> <li>• Lubrication..... 535</li> <li>• Plain Linear Bearings..... 535</li> <li>• Rolling Element Linear Bearings..... 537</li> <li>• Critical Considerations: Linear Bearings ..... 542</li> <li>• Best Practices: Linear Bearings ..... 542</li> </ul>		
<b>11.</b>	<b>Power Transmission Devices .....</b>	543
<b>11.1. Shafts .....</b>		547
<ul style="list-style-type: none"> <li>• Recommended Resources..... 547</li> <li>• Methods of Attachment ..... 547</li> <li>• Materials and Treatments..... 548</li> <li>• Deflection, Stress, and Fatigue..... 549</li> <li>• Critical Speeds ..... 556</li> <li>• Shaft Design Procedure ..... 558</li> <li>• Critical Considerations: Shafts. .... 562</li> <li>• Best Practices: Shafts..... 562</li> </ul>		
<b>11.2. Shaft Couplings .....</b>		563
<ul style="list-style-type: none"> <li>• Recommended Resources..... 563</li> <li>• Attachment to Shafts ..... 563</li> <li>• Shaft Misalignment ..... 564</li> </ul>		

• Coupling Types . . . . .	564
• Flexible Coupling Types . . . . .	567
• Coupling Selection . . . . .	570
• Critical Considerations: Shaft Couplings . . . . .	573
• Best Practices: Shaft Couplings . . . . .	573
<b>11.3. Gears . . . . .</b>	<b>574</b>
• Recommended Resources. . . . .	574
• Terms and Definitions . . . . .	575
• Gear Types . . . . .	582
• Gear Trains . . . . .	582
• Shaft Attachment Methods. . . . .	589
• Gear Quality Ratings . . . . .	589
• Backlash . . . . .	591
• Materials and Treatments. . . . .	595
• Lubrication and Wear. . . . .	596
• Spur Gears . . . . .	599
• Spur Gear Selection and Sizing. . . . .	599
• Helical Gears . . . . .	606
• Bevel Gears . . . . .	607
• Worm Gears . . . . .	608
• Critical Considerations: Gears . . . . .	612
• Best Practices: Gears. . . . .	612
<b>11.4. Gearboxes. . . . .</b>	<b>614</b>
• Recommended Resources. . . . .	614
• Gearbox Characteristics . . . . .	614
• Loads on Gearboxes. . . . .	616
• Gearbox Selection . . . . .	619
• Critical Considerations: Gearboxes. . . . .	626
• Best Practices: Gearboxes. . . . .	626
<b>11.5. Belts and Chains . . . . .</b>	<b>627</b>
• Recommended Resources. . . . .	627
• Drive Calculations . . . . .	627
<b>11.5.1 Belts . . . . .</b>	<b>629</b>
• Flat Belt Drive Design and Selection Procedure . . . . .	632
• V-Belt Drive Design and Selection Procedure . . . . .	636
• Synchronous Drive Design and Selection Procedure . . . . .	648
• Critical Considerations: Belts . . . . .	652
• Best Practices: Belts. . . . .	653
<b>11.5.2 Chains. . . . .</b>	<b>655</b>
• Chain Selection and Sizing. . . . .	658
• Critical Considerations: Chains . . . . .	662
• Best Practices: Chains . . . . .	663
<b>11.6. Lead, Ball, and Roller Screws . . . . .</b>	<b>664</b>
• Recommended Resources. . . . .	664

**xii** Complete Table of Contents

• Screw Characteristics .....	664
• Screw Stresses, Deflection, and Buckling .....	669
• Critical Speed .....	670
• Linear Motion Screw Types .....	671
• Lead Screws .....	673
• Ball Screws .....	674
• Lead or Ball Screw Selection Procedure .....	675
• Critical Considerations: Lead, Ball, and Roller Screws .....	680
• Best Practices: Lead, Ball, and Roller Screws .....	680
<b>12. Machine Reliability and Performance.....</b>	<b>681</b>
• Recommended Resources .....	683
• Machine Reliability .....	683
• Failure Modes, Effects, and Criticality Analysis .....	685
• Safety Category .....	693
• Manufacturing Equipment Performance .....	695
• Condition Monitoring .....	698
• Critical Considerations: Machine Reliability and Performance .....	698
• Best Practices: Machine Reliability and Performance .....	699

## ABOUT THE AUTHORS

**Jennifer Marrs, P.E.** has been working in industry as a mechanical design engineer for more than 18 years. Her focus has mainly been the design and analysis of high-speed assembly machines and related systems, but she has also worked as a product designer, manufacturing engineer, and forensic engineer. Jennifer holds a BSME from Worcester Polytechnic Institute, an MSME from Northeastern University, and volunteers with the mechanical engineering programs at both WPI and Dartmouth College. Jennifer has a successful consulting practice and is a licensed Professional Engineer in New Hampshire, Vermont, and Massachusetts. She is also a registered U.S. patent agent. Her employers and clients include Gillette, Millipore, FujiFilm Dimatix, and Green Mountain Coffee Roasters. Mrs. Marrs is currently on the Executive Committee of her local ASME subsection and holds one international patent.

### ***Contributing Authors:***

**Gregory Aviza** has over 18 years of industrial experience focusing on the design, building, and international commissioning of precision high-speed assembly automation. He has also worked as a product designer for the consumer goods industry and currently holds five U.S. and four international patents. He holds a BSME and MSME from Worcester Polytechnic Institute. Gregory currently works for the Gillette division of Procter & Gamble in the Front End Development Group where he is focused on developing the next generation of product and equipment designs. He can be reached through his Linked-In profile: [www.linkedin.com/in/aviza](http://www.linkedin.com/in/aviza)

**Charles A. Gillis, P.E.** has over 15 years of machine design experience, and currently works as a mechanical engineer for Gillette, the Blades & Razors division of Procter & Gamble. During this time, Charles has designed automated machinery for manufacturing Gillette's blade and razor products. He has designed and put into service numerous pieces of manufacturing equipment consisting of complex mechanisms of precision assembled components. He has designed equipment to manufacture the Gillette Mach3®, Venus®, Sensor3®, and Fusion® product lines. Charles holds a BSME from Worcester Polytechnic Institute and an MSME from Northeastern University. He is a licensed Professional Engineer in Massachusetts. In addition, Charles is a Geometric Dimensioning & Tolerancing instructor for Worcester Polytechnic Institute's Corporate and Professional Education department.

**E. Smith Reed, P.E.** is a forensic engineering consultant with over 30 years experience designing, testing, and putting into service mobile power machinery and industrial equipment. He is a Board Certified Forensic Engineer and is licensed as a Professional Engineer in Minnesota, New Hampshire, Alabama, South Carolina, and Florida (Mechanical, Industrial and

**xiv** About the Authors

Manufacturing Engineer). He has industrial/manufacturing and design engineering experience with Honeywell, Inc., Toro Co., Tennant Co., and Vermont Castings, Inc. Smith, a BSME graduate from the University of Arkansas, holds four U.S. patents. He is a member of several national engineering societies, including the Human Factors and Ergonomics Society, and serves on the board of directors of the National Academy of Forensic Engineers (formally affiliated with NSPE), also serving as its President.

## ACKNOWLEDGMENTS

My heartfelt gratitude and admiration goes out to my contributing authors, the team at Industrial Press, and the many individuals who provided content or guidance.

**Gregory Aviza**, contributing author, wrote the section on gears. He also read most of my early drafts, provided ideas, and gave advice that significantly improved the material. He was an essential resource and sounding board throughout this project.

**John Carleo**, Editorial Director at Industrial Press, believed in this project when it was nothing more than an idea. Over the course of a year and a half, he helped the idea grow significantly in scope. He always rapidly got me what I needed to keep improving and expanding the content.

**Charles A. Gillis, P.E.**, contributing author, wrote the chapter on precision locating and the section on tolerance analysis. His expert contributions to this book were essential and greatly appreciated.

**Christopher J. McCauley**, Senior Editor of *Machinery's Handbook*, spent countless hours providing practical guidance and technical support. He also patiently provided me with many images and other items from *Machinery's Handbook*. His advice and feedback was extremely valuable.

**E. Smith Reed, P.E.**, contributing author, wrote most of the chapter on safety and ergonomics. His expert contribution to this book was substantial and essential to the high quality and broad content of the chapter.

**Janet Romano**, Production Manager/Art Director at Industrial Press, did a fantastic job designing the layout and appearance of this book. Her expertise and hard work is visible on every single page, as well as on the cover.

**Robert Weinstein**, freelance developmental editor for Industrial Press, copyedited the manuscript and checked the final page proofs.

I would like to give additional thanks to the following people who provided either expert advice or essential material:

**Herb Arum**, SDP/SI ([www.sdp-si.com](http://www.sdp-si.com))

**William Bollig**, WITTENSTEIN ([www.wittenstein-us.com](http://www.wittenstein-us.com))

**Michael J. Brown**, A123 Systems, Inc. ([www.A123Systems.com](http://www.A123Systems.com))

**Robert S. Clippard, CFPPS**, Clippard Instrument Laboratory, Inc. ([www.clippard.com](http://www.clippard.com))

**Donald A. Cottrill**

**C. Wes Cross**, Westinghouse Electric Company, LLC ([www.westinghousenuclear.com](http://www.westinghousenuclear.com))

**Bruce Curry**, Penna Flame Industries ([www.pennaflame.com](http://www.pennaflame.com))

**xvi** Acknowledgments

**Wendy Earle**, SKF USA, Inc. ([www.skf.com](http://www.skf.com))

**Patrick Esposito**, Misumi USA, Inc. ([www.misumiusa.com](http://www.misumiusa.com))

**Sam Feller**, MIT Lincoln Laboratory ([www.ll.mit.edu](http://www.ll.mit.edu))

**Glenn Frazier**, Rockwell Automation, Inc. ([www.rockwellautomation.com](http://www.rockwellautomation.com))

**Nikki Groom**, igus, Inc. ([www.igus.com](http://www.igus.com))

**John Halvorsen**, SMC Corporation of America ([www.smcura.com](http://www.smcura.com))

**Todd Kanipe**, The Precision Alliance ([www.tpa-us.com](http://www.tpa-us.com))

**Dr. Kevin Lawton**, University of North Carolina, Charlotte ([www.uncc.edu](http://www.uncc.edu))

**Bill McCombe**, Curtis Universal Joint Company ([www.curtisuniversal.com](http://www.curtisuniversal.com))

**Eric J. Mann**, Graduate Student, Dartmouth College ([www.dartmouth.edu](http://www.dartmouth.edu))

**Corey Maynard, P.E.**, Proctor & Gamble ([www.pg.com](http://www.pg.com))

**Miriam Metcalfe**, WITTENSTEIN ([www.wittenstein-us.com](http://www.wittenstein-us.com))

**Robert L. Mott, P.E.**, Emeritus Professor, University of Dayton ([www.udayton.edu](http://www.udayton.edu))

**Bill Nartowt**, United County Industries Corp. ([www.countyheatreat.com](http://www.countyheatreat.com))

**Dr. Catherine Newman**, Industrial Product Design & Development Consultant

**Robert L. Norton, P.E.**, Worcester Polytechnic Institute ([www.wpi.edu](http://www.wpi.edu))

**Bill Oliver**, Minuteman Controls ([www.minutemancontrols.com](http://www.minutemancontrols.com))

**John Slocum**, SolidWorks Corp. ([www.solidworks.com](http://www.solidworks.com))

**Jason Sicotte**, Associated Spring Barnes Group Inc. ([www.asbg.com](http://www.asbg.com))

**Clifford M. Stover, P.E.**, California State Polytechnic University, Pomona ([www.csupomona.edu](http://www.csupomona.edu))

## INTRODUCTION

During more than 18 years as a machine designer, I have observed that experienced practitioners usually have assembled a collection of reference materials that they rely on constantly. This valuable cache usually includes standards, data tables, procedures, symbol definitions, component sizing guides, articles, and manufacturer's publications. Experienced designers also tend to have selected a few really great reference books and other resources like technical website links. This book attempts to summarize some of that useful information and present it in a practical way that maximizes on-the-job efficiency.

Meant for machine designers at all stages of their careers, this book contains materials that should be useful to all practitioners of machine design. However, it will be especially useful to designers in the automation, assembly equipment, and light industrial machine industries. For those at the start of their careers or in need of a refresher, I have attempted to include enough background information on each topic to allow the reader to use the procedures and formulas, and communicate effectively with suppliers. For the experienced practitioner, *Machine Designers Reference* is constructed to quickly and concisely deliver the tips, formulas, and data that are needed most often. Most formulas and data are tabulated to make them easy to find and use. All tables are indexed at the start of each chapter to quickly direct the reader to information that is frequently referenced. Bullet lists of best practices and critical considerations are provided for each topic.

The value of *Machine Designers Reference* will be enhanced when used in conjunction with the standard handbooks and textbooks of our time. It is expected that the reader will exercise good engineering judgment, perform detailed analysis when needed, and work closely with component manufacturers and shops. I have included a recommended resources list at the beginning of each section to assist the reader in locating excellent in-depth treatment of most subjects. The companies and websites mentioned within are resources that I have used in the course of my machine design work. The books are mostly those I own and use regularly.

When providing fastener or component information, I consulted the catalogs of several major distributors I have had experience with. I have included only the items and sizes most commonly used in light industrial machinery. To include all the data would make for a truly gigantic book. For more sizes and types of machine components, refer to a manufacturer's catalog or the applicable standards. I have also chosen to represent fractional inch sizes as decimal values. I have found that in the age of CAD, decimals are preferred.

Machine design is a global business, and many companies have converted to metric in the United States. This book is directed at U.S. designers using either the Imperial (English) or SI (metric) system of units. When presenting metric components, I have favored the ISO standards

## **xviii** Introduction

because in my experience ISO-designated components are more frequently encountered in light industry. I have chosen to use the decimal point rather than the comma in metric numbering to avoid confusion for anyone unfamiliar with metric convention. (A comma is the proper metric decimal indicator.)

The tabulated formulas contained in this book are designed to be convenient and quick to use for those experienced in the subject at hand. I have also found that they help me understand the interplay of variables and make better design decisions. For those following along with the written procedures in this book, I hope the tabulated formulas will be instructive, if not always convenient.

It is my intention that this book be easily used as a quick reference. The data tables for materials and fasteners are grouped together to assist in quickly locating and using the information when performing selection activities. I hope that readers will find that their appreciation for the groupings and ordering of the data tables grows as they use this book on the job.

New information and updates regarding this book and its contents are expected to be posted at [www.machinedesignersreference.com](http://www.machinedesignersreference.com) as they become available.

Any errata, comments, or suggestions that you can send to me at [info@industrialpress.com](mailto:info@industrialpress.com) would be greatly appreciated.

*Jennifer Marrs  
September, 2011*

# 10

## BEARINGS

## Contents

10.1	PLAIN BEARINGS	503
10.2	ROLLING ELEMENT BEARINGS	510
10.3	LINEAR BEARINGS	534

## Tables

10-1	PV Formulas for Rotary Sleeve Bearings	508
10-2	Typical Plain Bearing Material Properties	508
10-3	Applications and Suitable Bearings	519
10-4	Selected Bearing Types and Characteristics	520
10-5	Select Radial Bearing Tolerance Classes	521
10-6	Shaft Fits for Radial Bearings (ABEC/RBEC 1)	522
10-7	Housing Bore Fits for Radial Bearings (ABEC/RBEC 1)	523
10-8	Bearing Seat Geometric Tolerances	524
10-9	Loads On Rolling Element Bearings	528
10-10	Life and Load Ratings for Radial and Angular Contact Bearings	529
10-11	Static Load Safety Factors for Bearings	530
10-12	Shock Service Factors for Bearings	530
10-13	PV Formulas for Plain Linear Bearings	537
10-14	Life and Load Ratings for Linear Bearings	538



**Section**   
**10.1****PLAIN BEARINGS**

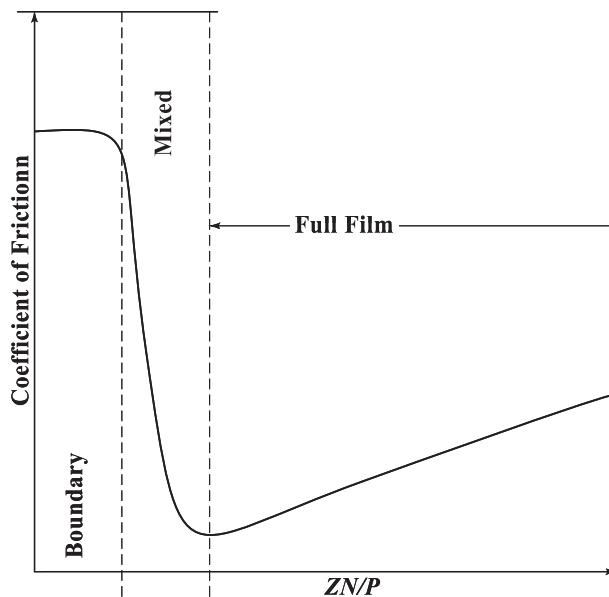
Plain bearings provide sliding contact between two surfaces. The most common type of plain bearing is the sleeve bearing or bushing. Plain bearings are often chosen over rolling element bearings due to cost or space limitations. They are also more rigid and quieter in operation than rolling element bearings. The main disadvantages of plain bearings are their higher potential to wear (as compared to rolling element bearings) as well as their relative vulnerability to contaminants. This section serves as a general introduction to plain bearings, with a focus on sleeve bearings used in rotary motion applications with boundary lubrication conditions. Please consult the recommended resources for more information and calculation methods for other types of lubrication. Plain bearings used in linear motion applications are discussed in Section 10.3.

**RECOMMENDED RESOURCES**

- R. Mott, ***Machine Elements in Mechanical Design***, 5th Ed., Pearson/Prentice Hall, Inc., Upper Saddle River, NJ, 2012
- R. L. Norton, ***Machine Design: An Integrated Approach***, 4th Ed., Prentice Hall, Upper Saddle River, NJ, 2011
- Oberg, Jones, Horton, Ryffel, ***Machinery's Handbook***, 28th Ed., Industrial Press, New York, NY, 2008

**LUBRICATION OF PLAIN BEARINGS**

Plain bearings must be lubricated in order to have long life and low friction. There are four types of lubrication conditions under which plain bearings are run: hydrostatic lubrication (full film), hydrodynamic lubrication (full film), mixed film lubrication, and boundary lubrication (thin film). Full film lubrication occurs when the lubricant layer between surfaces is thick enough to prevent any surface contact. Boundary lubrication occurs when the lubricant layer is present but not thick enough to prevent contact between surfaces. A graph showing relative coefficients of friction for the different types of lubrication are shown in Figure 10-1. The horizontal axis is a function of lubricant viscosity (Z), journal speed (N), and bearing pressure (P).



**Figure 10-1: Plain Bearing Lubrication vs. Coefficient of Friction**

Hydrostatic lubrication is full film lubrication, and occurs when high pressure lubricant is used to force the sliding surfaces apart. Plain bearings with hydrostatic lubrication can accommodate heavy loads at low speeds. Hydrostatic lubrication is normally used in planar or linear bearings rather than in sleeves. Design of an assembly using hydrostatic lubrication is extremely complex and must focus on lubricant feeding and containment. Hydrostatic lubrication is uncommon in light industry and is beyond the scope of this text.

Hydrodynamic lubrication is full film lubrication, and is most commonly employed with high-speed rotating shafts in plain sleeve bearings. Bearings with hydrodynamic lubrication are often called journal bearings. A wedge of lubricant is caught between the rotating shaft and bearing surface, providing sufficient pressure to carry the applied load. The shaft rides on a film of oil and does not contact the bearing except during periods of low speed or stasis. Typical coefficients of friction range from 0.002 to 0.010. Oil is typically used as the lubricant, and it must be supplied from a reservoir to maintain hydrodynamic lubrication. The lubricant also cools the bearing, and lubricant leakage and circulation enhances the cooling effect. Lubricant viscosity and temperature are important parameters in hydrodynamic lubrication performance, and temperature control is recommended. Hydrodynamically lubricated bearings go through periods of boundary lubrication during startup and shutdown periods. In light industrial machinery, relatively low speeds and/or intermittent movements mean

that boundary lubrication of plain bearings is more common than hydrodynamic lubrication. Hydrodynamically lubricated journal bearings are beyond the scope of this text, but are detailed in the recommended resources.

Mixed film lubrication occurs when the lubricant film thickness is slightly greater than the surface roughness of the surfaces. This is not hydrodynamic lubrication because the surfaces are close enough together to create drag and some surface contact. The conditions for mixed film lubrication are between those of hydrodynamic and boundary lubrication.

Boundary lubrication occurs at low speeds and/or high pressures. Surfaces in contact are partially separated by a lubricant film and partially in direct rubbing contact. Bearings with boundary lubrication have higher coefficients of friction and shorter life expectancy than hydrostatically or hydrodynamically lubricated bearings. To reduce friction and reduce wear, lubricant is usually embedded in the bearing and/or added to the shaft. Values of friction coefficients vary depending on bearing material and construction, but typically range from 0.05 to 0.20. Sleeve bearings designed to run well without added lubricants are often called "oil free" bearings, and generally have lubricant embedded in them, or lubricity is a property of the material. Many plastics, for instance, are inherently lubricious and can provide low coefficients of friction without additional lubrication. Plain bearings with boundary lubrication are common in the machinery industry and will be examined further in this section.

Lubricant is often applied to boundary lubricated bearings to extend life and reduce drag. Check the manufacturer's recommendations for recommended or prohibited lubricants. Grease is often used instead of oil in boundary lubrication applications because it's convenient to use, stays in place, and allows for simpler design. Grease and other fixed lubricants do nothing to cool the bearing, so relatively slow speeds are a must with boundary lubrication.

When the intention is to add lubricant to a plain bearing, provide for lubricant proliferation through the assembly, even when designing for boundary lubrication. In a fixed shaft arrangement, the shaft is often cross drilled and has an axial or a radial groove to allow lubricant to enter the bearing. A grease fitting or oil supply is often placed at one end of the shaft. In a rotating or sliding shaft arrangement, the lubricant supply is usually routed through the bearing housing and relies on a hole or a hole and groove to allow lubricant to enter the bearing. A grease fitting or oil supply is then placed on the bearing housing. When planning for hydrodynamic or hydrostatic lubrication, a thorough analysis of the lubricant circulation must be undertaken.

## BEARING MATERIALS FOR BOUNDARY LUBRICATION

Plain bearings designed to run with boundary lubrication are available in a variety of materials. There are many materials available, but the most common commercial bearing materials are tin, lead, bronze, copper, and plastic. Their general characteristics are as follows:

Bronzes and copper alloys: Bearings made of these materials are extremely common. They resist wear and temperature variation well. These bearings have a limited capacity to embed contaminants, so shaft scoring is a risk and requires shaft hardening. Alloys with higher lead content reduce shaft scoring and reduce friction during boundary lubrication, but will be more sensitive to elevated temperatures and require lower speeds. Copper alloy bearings often are available with dry lubricant embedded in the bearing surface. Sintered bronze bearings are porous and usually saturated with lubricant. Material properties vary, so consult the manufacturer's catalog for more information.

Plastics: In recent years plastic plain bearings have met or exceeded many characteristics of their metal counterparts. Plastic bearings can be formulated to meet a wide variety of requirements, including sanitary applications. When specifying a plastic bearing, it is important to consider that these bearings tend to run hotter than their thermally conductive metal counterparts. Elevated ambient temperatures can be of particular concern with plastic bearings. Confirm the temperature ratings of any plastic bearings with the manufacturer. It is important to note that some lubricants can attack plastic bearings or cause them to swell, so be sure to check material compatibility. Material properties vary greatly, so consult the manufacturer's catalog for more information.

## BOUNDARY LUBRICATED SLEEVE BEARINGS

Sleeve bearings used with boundary lubrication are very common in modern machine design. They are ideal for bearing applications requiring small radial clearances, quiet running, low speeds, and oscillating or intermittent movements. They are often available in straight and single flanged types (Figure 10-2). The flange can be used as a thrust bearing, and is also subject to boundary lubrication conditions. Sleeve bearings are most commonly pressed into a housing bore, but some have features for retaining the bearing with screws. Follow the manufacturer's recommendations for fits and tolerances of



**Figure 10-2: Plain Sleeve Bearings**

Source: igus Inc. ([www.igus.com](http://www.igus.com))

the bearing housing and shaft because proper fit is required to produce proper bore clearances, ensure even wear, and minimize drag.

Commercial catalogs often rate the load capacity of sleeve bearings intended for boundary and mixed film lubrication in terms of maximum allowable load, maximum allowable surface velocity, and PV factor. These values are used as maximum values to determine bearing size and materials. A safety factor of 2 is typical when examining PV factor. PV factor ratings will be highly variable depending on material, method of manufacture, and whether any embedded lubricants are present. Some manufacturers offer online software to select bearings and calculate life expectancy. One excellent example of such software can be found at [www.igus.com](http://www.igus.com).

Bearing pressure (P) is the radial force on the bearing divided by the projected area of contact. Projected area is equal to shaft diameter multiplied by length. Because PV is a function of bearing length, the use of a longer bearing is one method of getting the PV of the application lower than the PV rating for the bearing. In general, the length to bore ratio of plain sleeve bearings should never exceed 4:1.

PV factor is proportional to the heat of friction generated per unit of bearing area; it is used to measure the performance capability of a bearing. PV factor alone should not be used to size sleeve bearings. For low speed or high load applications, maximum allowable load will be the primary consideration. PV factor is calculated for rotating sleeve bearings according to the formulas in Table 10-1. Some common bearing material properties are listed in Table 10-2.

Selection of proper shaft material and hardness is critical for plain bearing and assembly performance. A smooth shaft surface makes the most of thin film lubrication and reduces friction. Sufficient hardness is essential to ensure that the shaft does not wear before the bearing does. A rule of thumb says that

**Table 10-1: PV Formulas for Rotary Sleeve Bearings**

<u>PV FACTOR</u>		<u>PV factor = P x V</u>
<b>INCH UNITS</b>  $P$ = Bearing pressure (psi) $F$ = Load on the bearing (lbf) $A$ = Bearing area ( $\text{in}^2$ ) $D$ = Bearing internal diameter (in) or shaft external diameter $L$ = Bearing length (in) $V$ = Bearing surface speed (ft/min) $N$ = Revolutions per minute $\theta$ = Swept angle of oscillation (radians) $f$ = Frequency of oscillation (oscillations per minute)		$P = \frac{F}{A}$ $A = DL$ Continuous rotation: $V = \frac{D\pi(N)}{12}$ Oscillating rotation: $V = \frac{\theta f D}{24}$
<b>METRIC UNITS</b>  $P$ = bearing pressure (MPa) $F$ = load on the bearing (N) $A$ = bearing area ( $\text{m}^2$ ) $D$ = bearing internal diameter (m) or shaft external diameter $L$ = bearing length (m) $V$ = bearing surface speed (m/min) $N$ = revolutions per minute $\theta$ = Swept angle of oscillation (radians) $f$ = Frequency of oscillation (oscillations per minute)		$P = \frac{F}{A(10^6)}$ $A = DL$ Continuous rotation: $V = D\pi(N)$ Oscillating rotation: $V = \frac{\theta f D}{2}$

**Table 10-2: Typical Plain Bearing Material Properties**

Bearing Material	Type	Temperature Range	Shaft Hardness	Dynamic P Max.	V Max.	PV Max
SAE 841 Bronze	Porous	10°F to 220°F	> 35 Rc	2,000 psi	1,200 ft/min	50,000 psi-ft/min
		-12°C to 104°C		14 MPa	6 m/s	1.8 MPa-m/s
SAE 660 Bronze	Non-porous	10°F to 450°F	> 35 Rc	4,000 psi	750 ft/min	75,000 psi-ft/min
		-12°C to 232°C		27 MPa	3.8 m/s	2.7 MPa-m/s
Nylon Plastic	Non-porous	10°F to 20°F	< 35 Rc	2,000 psi	600 ft/min	3,000 psi-ft/min
		-12°C to 93°C		14 MPa	3 m/s	0.11 MPa-m/s
PTFE Plastic	Non-porous	-350°F to 500°F	< 35 Rc	500 psi	50 ft/min	1,000 psi-ft/min
		-212°C to 260°C		3.5 Mpa	0.25 m/s	0.035 Mpa-m/s

the shaft should be 3 times harder than the bearing material. This difference in hardness ensures that any contaminant particles that enter the bearing will embed in the bearing material rather than score the shaft.

Hardened and ground steel shafts are generally recommended for use with bronze bearings. SAE 841 bronze bearings require steel shafts that have greater than 0.4% carbon content, such as SAE 1137 – 1141 steels. When corrosion protection is needed, hard chrome plating is a good choice. If stainless steel shafting must be used, choose a 400-series steel. When specifying stainless steel, a 416-series steel that is heat treated to maximum hardness is best. Shaft surface roughness should be 16 microinches (0.4 micrometers) or better.

Plastic bearings have different requirements depending on their makeup. Chrome plating may cause stick-slip behavior in some plastic bearings because

the surface finish is too fine. Stainless steel in the 300 series may be used with some plastic bearings. For plastic bearings, always follow the manufacturer's recommendations for shaft material, hardness, and surface roughness.

## SLEEVE BEARING SELECTION PROCEDURE FOR BOUNDARY LUBRICATION

When selecting a sleeve bearing, it can be beneficial to contact the manufacturers for application assistance. They often have specialists available to analyze the application and make recommendations to maximize bearing life and performance. The following procedure can be useful when selecting and sizing a sleeve bearing. This procedure assumes that the shaft is rotating in the bearing and there is boundary lubrication. This scenario is a very common one in light industrial machine design. Linear bearings are selected similarly, and are discussed in Section 10.3.

1. Determine the design parameters. These include the following:
  - Desired shaft diameter
  - Revolutions per minute of the shaft
2. Select a bearing length. A typical sleeve bearing should have a length of 1.5 to 2 times its inner diameter. An L/D as low as 1 is acceptable for some sintered bearings.
3. Select a bearing material. Compute the PV factor using the formulas in Table 10-1. Select a bearing in the desired size with a rated PV factor of at least twice (factor of safety) the computed value. Choosing a longer bearing will lower the PV factor for the application. Increasing the shaft size will also lower the PV factor.
4. Check the bearing maximum pressure rating. Verify that the chosen bearing maximum pressure rating is well above your calculated bearing pressure from Table 10-1. This includes checking the thrust load on the bearing flange if applicable.
5. Check the bearing maximum velocity rating. Verify that the chosen bearing maximum velocity rating is well above the calculated velocity of the shaft (journal) surface from Table 10-1.
6. Choose a bearing outer diameter. The bearing OD may already be set based on the results of previous steps. Once an OD is selected, verify that there is plenty of space for the OD of the chosen bearing in the bearing housing. Because the OD is generally pressed into the housing, avoid thin walls around the bearing.

**510 Chapter 10**

- Dimension and tolerance your shaft and bearing housing per the bearing manufacturer's recommendations. Specify the recommended shaft material and hardness. Add any required chamfers or radii, and specify any required surface finishes.

**CRITICAL CONSIDERATIONS: Plain Bearings**

- Plain bearing material selection is governed by the speed and loading conditions of the assembly.
- All plain bearings run under boundary lubrication conditions and will wear over time. Life can be maximized by staying well within the PV rating for the bearing.
- Shaft hardness and surface finish are critical for proper function and life expectancy.
- Heat is often the limiting factor with plastic bearings. This includes not only ambient temperature, but also the heat generated by friction during operation. Higher speeds generate more heat.
- Never store plain bearings with embedded lubricant in or on absorbent material, because the lubricant could wick out.

**BEST PRACTICES: Plain Bearings**

- Use a factor of safety of at least 2 when evaluating PV factors. This will ensure long bearing life.
- Add grease to plain bearings to prolong bearing life.
- Avoid ultra-soft bearing materials like PTFE unless absolutely needed. Soft materials are vulnerable to damage during installation and running, and tend to have shorter life spans than harder bearings.

**ROLLING ELEMENT BEARINGS**

Rolling element bearings are extremely common in machinery. They create rolling contact between two parts to minimize the effects of friction and enable high relative speeds with very little wear. The most common types of rolling element bearings are ring shaped and provide rolling contact between a shaft and a housing bore. Another common rolling element bearing is a

Section

**10.2**

thrust bearing that takes an axial load while rotating about a shaft or pin. Both types use either balls or rollers to carry the applied loads. Design of bearings is beyond the scope of this text. This section will focus on the types, selection, and sizing of commercially available steel ball and roller bearings.



## RECOMMENDED RESOURCES

- Juvinal, Marshek, ***Fundamentals of Machine Component Design***, 2nd Ed., John Wiley & Sons, Inc., New York, NY, 1991
- R. Mott, ***Machine Elements in Mechanical Design***, 5th Ed., Pearson/Prentice Hall, Inc., Upper Saddle River, NJ, 2012
- R. L. Norton, ***Machine Design: An Integrated Approach***, 4th Ed., Prentice Hall, Upper Saddle River, NJ, 2011
- Oberg, Jones, Horton, Ryffel, ***Machinery's Handbook***, 28th Ed., Industrial Press, New York, NY, 2008
- ***SKF General Catalogue***, SKF Group, June 2008
- ***ISO 281***: “Rolling bearings — Dynamic load ratings and rating life”
- ***American Bearing Manufacturers Association Website:***  
[www.americanbearings.org](http://www.americanbearings.org)

## LUBRICATION, SEALS, AND SHIELDS

Rolling element bearings must be lubricated to ensure long life and low drag. Bearings are normally lubricated with grease for speeds below 500 rpm at normal ambient temperatures. High speeds and high temperatures both require a circulating oil lubrication system to keep the bearing cool. Manufacturers will normally specify the appropriate lubricant for each bearing.

Seals are available in many formats, but in general all are capable of fully sealing the bearing from contaminants and retaining lubricant in the bearing. “Lubricated for life” or “maintenance free” are phrases commonly used to describe rolling element bearings that have seals and are pre-lubricated at the manufacturer. If seals are not available for a bearing, provisions must be made in the assembly to direct and retain lubricant at the bearing. Some bearing manufacturers also sell a line of externally mounted seals for bearing arrangements.

Shields are intended to protect the bearing from large contaminants and accidental contact damage. They are generally metal and do not form a

**512** Chapter 10

complete seal around the bearing. Bearings can have just seals, just shields, or both seals and shields. Not all bearings are available with seals or shields. Separable bearings are not sealed. In general, seals are available for deep groove ball bearings, angular contact ball bearings, self-aligning ball bearings, cylindrical roller bearings, needle roller bearings, and spherical roller bearings.

## BEARING CHARACTERISTICS

Rolling element bearings are generally made up of two rings, called "races," separated by a set of rolling elements. Radial bearings are composed of an inner and outer race, whereas thrust bearings are composed of two (or more, in the case of double direction bearings) races. Rolling elements can be balls, cylindrical rollers, tapered rollers, or other specialized shapes.

A bearing cage is an internal component that captivates each rolling element in the bearing and prevents contact between individual rolling elements. Not all bearings have cages. Whether a bearing does or not will be clearly stated by the manufacturer. Cages help reduce internal friction in the bearing and ensure that the load bearing elements are evenly distributed for smooth running. "Full complement" bearings normally forego a cage so that more rolling elements can be fit into the bearing for greater load capacity. Cages are not always metal, so material and thermal compatibility must be verified if using caged bearings.

Some types of bearings, such as cylindrical roller bearings, are capable of axial displacement between the inner and outer races. When axial displacement is a function of the bearing, the maximum allowable displacement will be provided in the catalog information. Axial displacement can occur during normal running conditions as the shaft warms and elongates. This effect must be accommodated in the bearing arrangement through the use of either a bearing that allows axial displacement, or by designing the bearing arrangement and fits so that one bearing can easily move axially in its housing.

Most radial bearings are made with a cylindrical bore which is meant to be mounted on a cylindrical shaft. Some bearings are available with a tapered bore that is designed to be mounted on an adapter sleeve or tapered shaft. A tapered bore allows the bearing to be adjusted to remove internal clearance from the bearing. Cylindrical bores are much more commonly used and will be assumed for the purposes of this text unless otherwise specified. See the recommended resources for more information on the use of tapered bores.

Some bearings are separable, which means the inner and outer races can be separated axially from each other. Tapered roller bearings are a

common example of separable bearings. Separability eases installation, but generally precludes integral sealing.

Temperature rating is not always stated in catalogs. In general, catalog values for life, speed, and loading assume an ambient temperature of 68°F (20°C). Most standard steel bearings have a maximum temperature of 250°F (121°C). The maximum temperature must include the elevated temperature of the bearing due to running conditions and friction.

Limiting speed is usually provided in catalog data for bearings. In all cases, the limiting speed should never be exceeded. The bearing can run up to limiting speed, but only for short periods of time. The reference or operating speed rating normally represents the speed at which the heat generated by the bearing is in equilibrium with the heat dissipated. It is assumed that operating above the rated speed for any length of time will cause the bearing to overheat. Reference or operating speed ratings are usually given for bearings in catalogs. Both the limiting and operating speed ratings assume a given set of operating and lubricant conditions. The standard ISO 15312: 2003 provides a set of reference conditions for the operating speed rating, which include an ambient temperature of 20°C (68°F), a bearing temperature of 70°C (158°F), and a constant load. These conditions also assume that the inner ring of the bearing is rotating. When the outer ring rotates, the speed ratings should be lowered. Note that when a bearing is operated at a very low speed or undergoes oscillating movements rather than continuous running, hydrodynamic lubrication does not occur in the bearing. In those cases, lubricants should be used that form a film on the bearings. Lubricants with EP additives form such a film.

Internal clearance is defined as the total distance that one race can be moved relative to the other in the stated direction. Bearings have radial and axial internal clearances. Normal clearance bearings are typically used and must be mounted with the recommended standard fits on the shaft and housing. If different mounting fits are used, the bearing must have a different internal clearance in order to work properly. Bearings with less internal clearance are available commercially for ultra-precision applications.

Basic dynamic load rating is the load for which each bearing is expected to meet its life expectancy. Static load rating is the maximum load the bearing can withstand without internal damage. These load ratings are discussed in more detail later in this section.

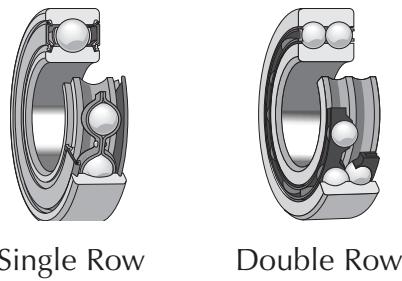
## 514 Chapter 10

Starting torque is the minimum torque required to start a bearing rotating from rest. For small instrument bearings, starting torque and bearing friction is of concern. The addition of seals will increase starting torque as well as running friction. Values for starting torques and friction calculations can be found in manufacturer's data.

### BEARING TYPES

The most common bearings in light industrial machine design are deep groove, angular contact, cylindrical roller, and spherical roller bearings. Deep groove ball bearings are by far the most commonly used type of rolling element bearing. The following are descriptions of some of the bearings found in machinery.

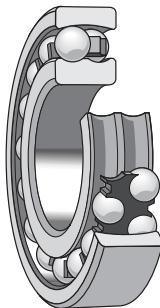
Deep groove ball bearings (Figure 10-3) are extremely versatile and are available fully lubricated and sealed. They can accommodate some axial loading in both directions and are capable of high speeds. They can be used as the locating bearing in bearing arrangements. Deep groove ball bearings typically can accommodate angular misalignment between 2 and 10 minutes of arc. Verify this with the manufacturer for every bearing. Double row deep groove ball bearings are used when the load capacity of single row deep groove ball bearings is insufficient. Their ability to handle axial loads and misalignment is about the same as that of single row bearings.



**Figure 10-3: Deep Groove Ball Bearings**

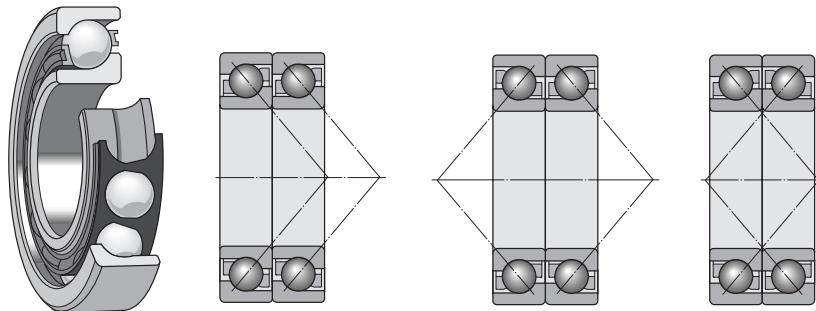
Source: SKF USA Inc. ([www.skf.com](http://www.skf.com))

Self-aligning ball bearings (Figure 10-4) were invented by SKF USA Inc. These bearings have a double row of balls that ride in a spherical raceway. This type of bearing is capable of high speeds and is particularly suited for applications with significant angular misalignment. Misalignment up to 3 degrees is allow-

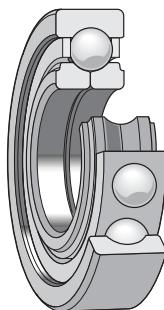
**Figure 10-4: Self-Aligning Ball Bearing**Source: SKF USA Inc. ([www.skf.com](http://www.skf.com))

able with some bearings. Verify this with the manufacturer for every bearing. Self-aligning ball bearings are available with seals.

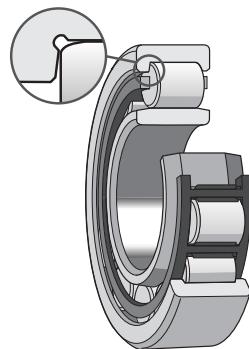
Angular contact ball bearings (Figure 10-5) are designed to handle combined loading. They are available in single and double row configurations. A single row angular contact ball bearing can handle axial loading in only one direction. These bearings are normally applied in a pair, arranged back to back, and adjusted against each other to provide a stiff arrangement that can handle axial loads in both directions, as well as radial loads and tilting moments. Angular contact ball bearings have a very limited ability to accommodate angular misalignment.

**Figure 10-5: Angular Contact Ball Bearings**Source: SKF USA Inc. ([www.skf.com](http://www.skf.com))

Four-point contact ball bearings (Figure 10-6) are single-row, angular contact ball bearings that have special raceways designed to allow the bearing to support axial loads in both directions. These bearings are meant for applications with predominantly axial loads and can support only limited radial loading.

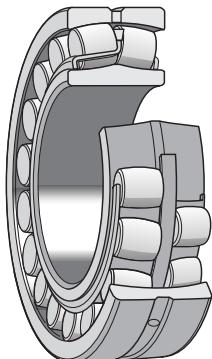
**516** Chapter 10**Figure 10-6: Four-Point Contact Ball Bearing**Source: SKF USA Inc. ([www.skf.com](http://www.skf.com))

Cylindrical roller bearings (Figure 10-7) are available in many different configurations. The most common configuration consists of a single row of cylindrical rollers, caged, with an inner race that is axially displaceable. These bearings are suitable for very heavy radial loads and can operate at high speeds. Cylindrical roller bearings are not suitable for axial loads and can accommodate angular misalignment up to only a few minutes of arc. These bearings are generally not used to locate a shaft axially, but special designs are available that allow the bearing to be used as a locating bearing.

**Figure 10-7: Cylindrical Roller Bearing**Source: SKF USA Inc. ([www.skf.com](http://www.skf.com))

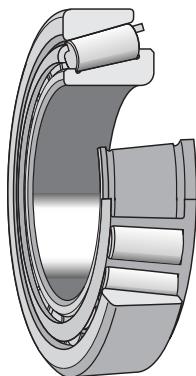
Spherical roller bearings (Figure 10-8) are comprised of a double row of rollers within a spherical raceway. They are capable of accommodating significant angular misalignment up to about 3 degrees. Verify this with the manufacturer for every bearing. These bearings can handle heavy radial and axial loads acting in both directions. Sealed versions are available.

Tapered roller bearings (Figure 10-9) are available in a variety of configurations. These bearings have tapered rollers that are arranged at an angle to the



**Figure 10-8: Spherical Roller Bearing**

Source: SKF USA Inc. ([www.skf.com](http://www.skf.com))



**Figure 10-9: Tapered Roller Bearing**

Source: SKF USA Inc. ([www.skf.com](http://www.skf.com))

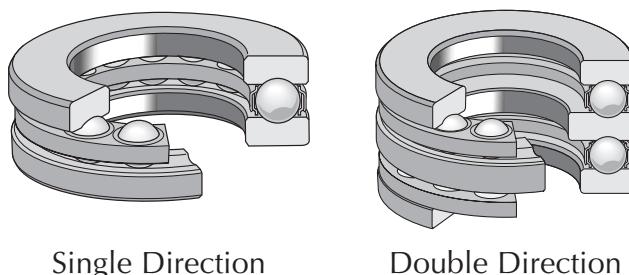
bore. Tapered roller bearings are particularly suitable for significant combined loading, but can accommodate axial loads in only one direction. Single-row tapered roller bearings are generally separable and are most often used in pairs arranged such that axial loads in both directions can be borne. Single-row tapered roller bearings can accommodate angular misalignment only up to a few minutes of arc. These bearings are usually preloaded at installation and require special care to install and run in.

Needle roller bearings are ideal for applications where radial space is limited. They have rollers that are very long and thin. These bearings have high radial load capacities, but cannot tolerate axial loads. These bearings are very intolerant of angular misalignment. Needle roller bearings are sometimes used without an inner race. This provides an even more compact bearing solution, but special care must be taken in the manufacture of the shaft that will become the inner race.

**518** Chapter 10

**Figure 10-10: Ball Thrust Bearings**

Source: SKF USA Inc. ([www.skf.com](http://www.skf.com))



Ball thrust bearings (Figure 10-10) are designed for axial loads only. Single-direction thrust bearings have a single row of balls and can handle axial loading in only one direction. Double-direction thrust bearings, as the name suggests, can handle axial loading in both directions and have two rows of balls. These bearings are generally separable.

Cylindrical roller thrust bearings have cylindrical rollers and are designed to handle axial loads acting in one direction only. These bearings are ideal for heavy axial loading and are fairly compact.

Spherical roller thrust bearings use spherized rollers arranged at an angle to the shaft axis to transmit loading. This enables the bearing to handle both axial and radial loading. These bearings are self-aligning and can handle angular misalignments up to 3 degrees. Verify this with the manufacturer for every bearing.

Needle roller thrust bearings are ideal for supporting heavy axial loads in a minimum of axial space. These bearings are similar to cylindrical roller thrust bearings in that they are intolerant of misalignment, cannot support radial loads, and are available in single-direction or double-direction versions. When space is at an absolute premium, the needles and cage can be used without upper and lower races. In this situation, the abutting parts must be carefully manufactured to serve as races.

Some common application conditions are listed in Table 10-3 with one or more suitable bearing types. Table 10-4 lists some of the commonly available bearing types and a few key characteristics. There are many more bearing types and options available. It is important to note that rolling element bearings are less appropriate than plain bearings for applications where the angle of rotation is small; for example, a shaft that undergoes a small oscillating motion. Rolling element bearings in such an application would lubricate and wear unevenly, causing premature failure.

***Table 10-3: Applications and Suitable Bearings***

<b>Application Condition</b>	<b>Typical Bearing Types</b>
High Misalignment	Self-Aligning Ball Bearings, Spherical Roller Bearings
Bearing Used To Locate Shaft Axially	Angular Contact Bearings, Deep Groove Ball Bearings (Light axial load only)
High Speeds (Radial Loads Only)	Deep Groove Ball Bearings, Self-Aligning Ball Bearings
High Speeds (Combined Loads)	Angular Contact Bearings
Light to Moderate Radial Loads	Deep Groove Ball Bearings
Heavy Radial Loads	Cylindrical Roller Bearings, Needle Roller Bearings
Combined Loads, Radial Dominant	Angular Contact Bearings, Tapered Roller Bearings
Combined Loads, Axial Dominant	Spherical Roller Thrust Bearings
Light to Moderate Axial Loads	Thrust Ball Bearings, Four-Point Contact Bearings
Heavy Axial Loads	Roller Thrust Bearings
Moment Loads	Paired Angular Contact Ball Bearings, Face-To-Face Tapered Roller Bearing Pair
Axial Displacement Expected	Cylindrical Roller Bearings, Needle Roller Bearings
Low Profile	Needle Roller Bearings
Maximum Stiffness	Cylindrical Roller Bearings, Tapered Roller Bearings, Needle Roller Bearings

**Table 10-4: Selected Bearing Types and Characteristics**

Bearing Type	Typical Application	Characteristics of Bearing								
		Axial Load Capability	Radial Load Capability	Moment Load Capability	Accommodates Misalignment	Internal Axial Displacement	High Stiffness	Seals Available	Low Profile	Separable
Deep Groove Ball Bearing	General Use, Moderate Radial, Light Axial Loads	●	●		●		●			
Deep Groove Ball Bearing (Double Row)	Heavy Radial Loads	●	●							
Self-Aligning Ball Bearing	High Misalignment	●	●		●		●			●
Angular Contact Ball Bearings	Unidirectional Combined Loads	●	●		●					
Angular Contact Pair (Back To Back)	Bidirectional Combined Loads	●	●	●				○		
Four-Point Contact Ball Bearings	Light Axial Loads	●							●	
Cylindrical Roller Bearings	Heavy Radial Loads		●		●	●	●		●	
Full Complement Cylindrical Roller Bearings	Very Heavy Radial Loads		●		●	●	●		○	
Needle Roller Bearings	Low Profile		●		●	●	●	●	●	
Spherical Roller Bearings	High Misalignment, Heavy Combined Loads	●	●		●		●			●
Taper Roller Bearings	Unidirectional Combined Loads	●	●		●		●		●	
Taper Bearing Pair (Face to Face)	Bidirectional Combined Loads	●	●	●	●		●		●	
Thrust Ball Bearings	General Use, Thrust	●							●	
Cylindrical Roller Thrust Bearings	Heavy Loads, Thrust	●							●	
Needle Roller Thrust Bearings	Low Profile, Thrust	●						●	●	
Spherical Roller Thrust Bearings	High Misalignment, Thrust	●	●		●				●	

## RADIAL BALL AND ROLLER BEARING DIMENSIONS AND TOLERANCES

Rolling element bearing dimensions and tolerances are heavily standardized. The Anti-Friction Bearing Manufacturers Association (AFBMA) and ISO have standards that are in agreement. Bearings from different manufacturers are generally interchangeable as a result. The Annular Bearing Engineers Committee (ABEC) defines the standard tolerances for bearings in the United States, and ISO standards are in agreement for metric bearings. Radial ball and roller bearings have five standard classes of tolerances, which are given in Table 10-5. Higher precision levels yield a longer life expectancy, but come

**Table 10-5: Select Radial Bearing Tolerance Classes**

Application	ANSI/ABMA Standard 20 Tolerance Class		ISO 492 Tolerance Class
	Ball Bearings	Roller Bearings	
Standard	ABEC 1	RBEC 1	Normal
Semi-Precision	ABEC 3	RBEC 3	Class 6
Precision	ABEC 5	RBEC 5	Class 5
High Precision	ABEC 7	RBEC 7	Class 4
Ultra Precision	ABEC 9	RBEC 9	Class 2

at a higher cost. Most machinery applications will use ABEC 1 class bearings. Applications that require extra smooth and accurate shaft running may require ABEC 5 or even ABEC 7 bearings. For tolerance values in each class, consult the recommended resources.

Machine designers will primarily be concerned with the dimensions they have control over: shaft diameter and housing bore diameter. In general, a light press fit on the rotating race is sought for bearing mounting. The rotating race is generally the inner race, but not always. It is essential to apply the appropriate fits to the shaft and housing because the bearing internal clearance in operation relies on the proper mounting fits. For bearings with an ABEC 1 (standard) tolerance class, Tables 10-6 and 10-7 are useful for determining the appropriate tolerances for the shaft and housing bore. For other types of bearings, such as needle roller bearings, consult with the manufacturer on tolerance information. It is typical for manufacturers to specify tolerances on bearing features and recommend tolerances for mating parts. These tolerances are typically very small (a few ten-thousandths of an inch) and are the responsibility of the machine designer.

Bearing seats should generally be ground and have a surface roughness of 16 to 32 microinches (0.4 to 0.8 micrometers). Maximum fillet dimensions for shoulders and steps are normally provided for each bearing in the manufacturer's catalog. Larger fillet radii reduce stress concentrations, so be sure to take advantage of the fillet allowance.

Proper geometric tolerancing of the shaft and housing bearing seats is essential for proper bearing fit and function. Both the diameters and the perpendicular abutments must be tightly controlled. Recommended geometric tolerances for metric bearing seats and abutments are shown in Table 10-8. IT (International Tolerance) grades are provided; they can be used to determine the numerical tolerances. The numerical values for tolerance grades are provided in Section 3.1 of this book. For cylindricity and total radial runout, the numerical tolerance represented by the tolerance grade is divided by 2 as shown.

**Table 10-6: Shaft Fits for Radial Bearings (ABEC/RBEC 1)**

Numerical values for tolerance designations are given in Section 3.1

Operating Conditions			Ball Bearings		Cylindrical Roller Bearings		Spherical Roller Bearings		ISO Tolerance Designation (a)
			mm	inch	mm	inch	mm	inch	
Inner Ring Stationary w/Respect to Load	All Loads	Inner ring has to be easily displaceable	All Diameters	All Diameters	All Diameters	All Diameters	All Diameters	All Diameters	g6
		Inner ring does not have to be easily displaceable	All Diameters	All Diameters	All Diameters	All Diameters	All Diameters	All Diameters	h6
RADIAL LOAD			NOMINAL SHAFT DIAMETER						
Inner Ring Rotating w/Respect to Load or Direction of Load Indeterminate	LIGHT: Loads up to 0.075C (C = dynamic load rating)	$\leq 18$	$\leq 0.71$						
		$> 18$	$> 0.71$	$\leq 40$	$\leq 1.57$	$\leq 40$	$\leq 1.57$	h5	
				(40) - 140	(1.57) - 5.51	(40) - 100	(1.57) - 3.94	j6 (b)	
				(140) - 320	(5.51) - 12.6	(100) - 320	(3.94) - 12.6	k6 (b)	
	NORMAL: Ball: 0.075C to 0.15C Cylindrical Roller: 0.075C to 0.2C Spherical Roller: 0.075C to 0.25C (C = dynamic load rating)	$\leq 18$	$\leq 0.71$					m6 (b)	
		$> 18$	$> 0.71$	$\leq 40$	$\leq 1.57$	$\leq 40$	$\leq 1.57$	j5	
				(40) - 100	(1.57) - 3.94	(40) - 65	(1.57) - 2.56	k5	
				(100) - 140	(3.94) - 5.51	(65) - 100	(2.56) - 3.94	m5	
				(140) - 320	(5.51) - 12.6	(100) - 140	(3.94) - 5.51	n6	
				(320) - 500	(12.6) - 19.7	(140) - 280	(5.51) - 11.0	p6	
	HEAVY: Loads over 0.15C (C = dynamic load rating)	$(18) - 100$	$(0.71) - 3.94$					k5	
		$> 100$	$> 3.94$	$\leq 40$	$\leq 1.57$	$\leq 40$	$\leq 1.57$	m5	
				(40) - 65	(1.57) - 2.56	(40) - 65	(1.57) - 2.56	m6 (b)	
				(65) - 140	(2.56) - 5.51	(65) - 100	(2.56) - 3.94	n6 (b)	
				(140) - 200	(5.51) - 7.87	(100) - 140	(3.94) - 5.51	p6 (b)	
				(200) - 500	(7.87) - 19.7	(140) - 200	(5.51) - 7.87	r6 (b)	
Pure Thrust Load			All Diameters	All Diameters	Consult Manufacturer				j6 (b)

a) Tolerances are shown for solid steel shafts. For hollow or nonferrous shafts, tighter fits may be needed.

b) When greater accuracy is required, use j5, k5, and m5 instead of j6, k6, and m6, respectively.

**Table 10-7: Housing Bore Fits for Radial Bearings (ABEC/RBEC 1)**  
Numerical values for tolerance designations are given in Section 3.1

Design and Operating Conditions				ISO Tolerance Designation (a)
Rotational Conditions	Loading	Outer Ring Axial Displacement Limitations	Other Conditions	
Outer Ring Stationary w/Respect to Load	Light, normal, and heavy	Outer ring must be easily displaceable axially	Heat input through shaft	G7
	Shock with temporary complete unloading	Transitional range (c)	Housing split axially	H7 (b)
	Light and normal		Housing not split axially	H6 (b)
Load Direction is Indeterminate	Normal and heavy		J6 (b)	J6 (b)
	Heavy shock			K6 (b)
	Light	Outer ring need not be axially displaceable	Split housing not recommended	M6 (b)
Outer Ring Rotating w/Respect to Load	Normal and heavy			N6 (b)
	Heavy		Thin wall housing not split	P6 (b)

a) For cast iron or steel housings. For nonferrous alloy housings tighter fits may be needed.

b) Where wider tolerances are permissible, use tolerances P7, N7, M7, K7, J7, and H7

c) The tolerance zones are such that the outer ring may be either tight or loose in the housing.

**Table 10-8: Bearing Seat Geometric Tolerances**

Accuracy of form and position for bearing seatings on shafts and in housings						
Surface Characteristic	Symbol for characteristic	tolerance zone	Permissible deviations Bearings of tolerance class <sup>1)</sup>			
<b>Cylindrical seating</b>			Normal CLN	P6	P5	
Cylindricity		$t_1$	IT5/2	IT4/2	IT3/2	IT2/2
Total radial runout		$t_3$	IT5/2	IT4/2	IT3/2	IT2/2
<b>Flat abutment</b>						
Rectangularity		$t_2$	IT5	IT4	IT3	IT2
Total axial runout		$t_4$	IT5	IT4	IT3	IT2
Explanation						
For normal demands	For special demands with respect to running accuracy or even support					

<sup>1)</sup>For bearings of higher accuracy (tolerance class P4, etc.), please consult with the manufacturer.

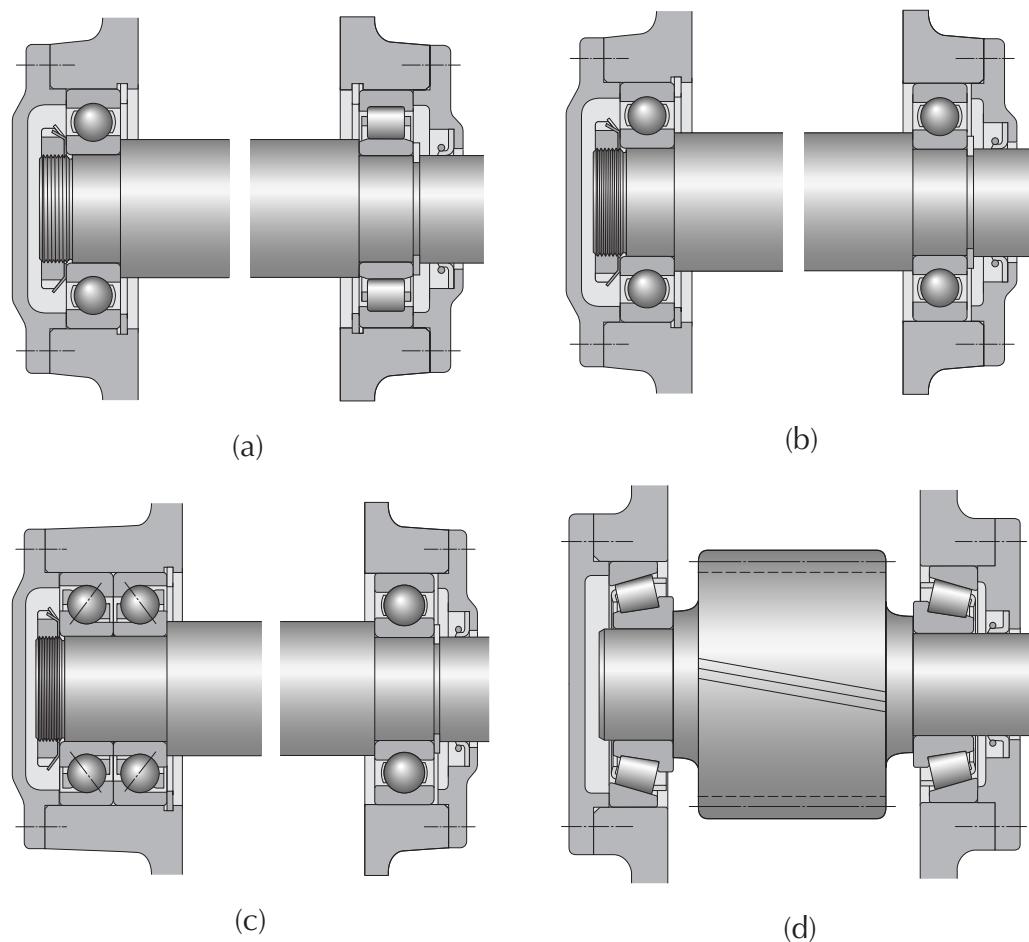
Source: SKF USA Inc. ([www.skf.com](http://www.skf.com))

## BEARING ARRANGEMENTS

Bearing arrangements can be broken into two basic types: preloaded and non-preloaded. Most bearing arrangements found in light industrial machinery will be of the non-preloaded variety. Preloaded bearing arrangements are often found in machine tools and other extremely high accuracy applications. Preloading is also called for when a bearing is run under extremely light loading conditions at high speeds. Preloading may be accomplished using springs or by adjusting two bearings against each other, using spacers, until zero operational clearance is achieved. Preloading is beyond the scope of this text, but is detailed in the recommended resources.

A non-preloaded bearing arrangement generally includes two bearings and associated hardware that support and locate a shaft, both radially and axially. Normally just one bearing, called the locating bearing, is tasked with axial location of the shaft in both directions. The locating bearing (or bearing combination) necessarily must be able to handle combined axial and radial loading. Suitable locating bearings include deep groove ball bearings when axial loading is light, angular contact bearings, spherical roller bearings, or a matched pair of tapered roller bearings. The second (non-locating) bearing usually constrains the shaft only radially. This type of arrangement requires that the locating bearing be axially and radially fixed on both the shaft and housing, while the other is allowed to float in the axial direction. Allowing one bearing to float axially prevents overloading of the bearings due to shaft expansion. If the non-locating bearing is of a type that allows axial displacement within the bearing, as do some types of cylindrical roller bearings, the bearing races may be axially constrained without fear of overloading.

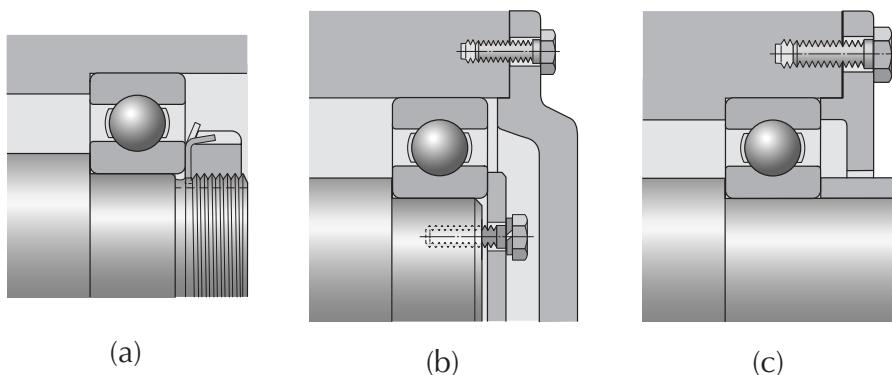
Figure 10-11a shows a bearing arrangement consisting of a deep groove ball bearing and a cylindrical roller bearing capable of internal axial displacement. In this situation, both bearings may be fully captivated. Figure 10-11b shows an arrangement using two deep groove ball bearings. In this case, the non-locating bearing is free to move in the housing and allow axial displacement. Figure 10-11c illustrates an arrangement using two opposed angular contact bearings to locate the shaft axially, while a deep groove bearing is allowed to move axially in its housing. Figure 10-11d shows a pair of tapered roller bearings locating and supporting a shaft. In this type of arrangement, the bearing housings must be axially adjusted relative to one another to achieve proper preload on the bearings.



**Figure 10-11: Typical Bearing Arrangements**

Source: SKF USA Inc. ([www.skf.com](http://www.skf.com))

Axial constraint of bearings cannot be accomplished merely through the bearing fit on the shaft and in the housing. When a bearing with a cylindrical bore must be located axially on a shaft, this is usually accomplished using a shoulder on the shaft. Another component, such as a nut, collar, or retaining ring, is used to captivate the bearing race against the shaft shoulder. This location method is illustrated in Figure 10-12a and b. The shoulder and other hardware must be properly sized to fully support the inner race without interfering with bearing rotation. The outer race of a bearing is normally captured between a shoulder in the housing bore and a clamping ring attached to the housing (Figure 10-12c). Bearings with tapered bores are less commonly used and require the use of adapter sleeves and spacers to mount and locate properly. Consult the recommended resources for information on installation of tapered bore bearings.



**Figure 10-12: Typical Axial Bearing Location Methods**

Source: SKF USA Inc. ([www.skf.com](http://www.skf.com))

## LOADS ON BEARINGS

Axial and radial load carrying capacities are highly variable among different types of bearings. Many radial bearings have very limited axial load carrying capability. Some bearings can carry axial loads in only one direction. The size and direction of applied loads is of primary concern when selecting a bearing type.

When selecting and sizing a bearing, one must first quantify the axial and radial loads seen by the bearing during operation. Section 11.1 of this text includes some formulas for calculating loads on a shaft for common machine elements. Two types of loading on each bearing must be evaluated: static loading and dynamic loading. Static loading must take into account any maximum loads seen by the bearing, even if only for a short length of time. Dynamic loading considers normal operation loads. In both cases, an equivalent load must be calculated for the bearing. The equivalent static and dynamic loads are then compared with catalog static and dynamic load ratings to select the appropriate bearing.

Equivalent load is a function of both the loading on the bearing and the bearing configuration. Pure thrust bearings have an equivalent axial load equal to the applied axial load, and the radial load must be zero. Purely radial bearings have an equivalent radial load equal to the applied radial load and the axial load must be zero. Bearings designed for combined loading, like angular contact bearings, are configured such that applied axial loads induce radial loads, and applied radial loads induce axial loads. This means that even a purely axial or radial load condition will result in combined loading on the bearing. In many applications, a combined axial and radial applied load is present. Based on the bearing type and configuration, an equivalent load must

**Table 10-9: Loads On Rolling Element Bearings**

$F_R$ = applied radial load		$F_A$ = applied axial (thrust) load	
<b>FLUCTUATING LOADS</b>		Speed, load direction constant: $F_R = \frac{F_{R\min} + 2F_{R\max}}{3}$ $F_A = \frac{F_{A\min} + 2F_{A\max}}{3}$	
<b>RADIAL BEARINGS AND SPHERICAL ROLLER BEARINGS</b>		<b>STATIC EQUIVALENT LOAD</b> $W$ = Consult manufacturer's catalog $Z$ = Consult manufacturer's catalog  <b>DYNAMIC EQUIVALENT LOAD</b> $V = 1$ if inner bearing race rotates $V = 1.2$ if outer bearing race rotates $e$ = Consult manufacturer's catalog $X$ = Consult manufacturer's catalog $Y$ = Consult manufacturer's catalog	Load direction rotating: $F_R = f_m(F_c + F_r)$ $F_c$ = Constant direction load $F_r$ = Rotating direction load $0.75 \leq f_m \leq 1$ (See manufacturer)  $F_{MAX} = WF_R + ZF_A$ If $F_{MAX} < F_R$ then $F_{MAX} = F_R$
<b>ANGULAR CONTACT BEARINGS AND TAPERED ROLLER BEARINGS</b>		<b>EQUIVALENT LOAD</b> Note: Radial loads on angular contact and tapered roller bearings induce axial loads. Consult with the manufacturer for axial load calculation methods.	Radial Load Only: $F = VF_R$ Combined Radial And Thrust Loads: $F = VXF_R + YF_A$ Test For Relatively Small Thrust: $\frac{F_A}{VF_R} \leq e$ Then $X = 1, Y = 0$
<b>THRUST BEARINGS</b>		<b>EQUIVALENT LOAD</b>	Axial (Thrust) Load Only: $F = F_A$ Radial or Combined Loads: Consult manufacturer

be calculated from the applied loads. The formulas in Table 10-9, in combination with the manufacturer's catalog data, can be used to accomplish this.

Most bearings must be subjected to a minimum load in order to function properly (have the rolling elements roll inside the bearing rather than slide) and reach their expected lifespans. In most cases, the weight of the components is enough to meet this minimum load requirement. When dealing with very light components and loads, consult the manufacturer for calculation methods for minimum load requirements. A rule of thumb is to apply a minimum load of  $0.01C$  to ball bearings and  $0.02C$  to roller bearings.  $C$  is the dynamic load rating for the bearing, which is provided in catalogs and calculated in Table 10-10.

The radial loads used in Table 10-9 are assumed to be in a constant direction. When a load varies, its mean value must be determined and used as the load value in life and dynamic load calculations. When a load fluctuates while its direction is fairly constant, its mean value can be estimated using the

equation in Table 10-9. If the direction of the load or part of the load rotates, as with an unbalance condition, the mean load can be calculated using the equation in Table 10-9.

## BEARING LOAD RATINGS AND LIFE EXPECTANCY

Life expectancy is a statistical phenomenon. Basic dynamic load rating is typically defined as the load at which 90% of a population of identical bearings will complete 1 million revolutions without failure. This may vary among manufacturers, so it is essential to verify the assumptions behind any catalog information. Most manufacturers follow the standard ISO 281: 1990 which contains bearing life and dynamic load calculation methods. Life calculations based on the standard can be found in Table 10-10. Part of load calculation involves applying a service factor (Table 10-12) which accounts for shock loading in service.

**Table 10-10: Life and Load Ratings for Radial and Angular Contact Bearings**

$L$ = Life expectancy in revolutions $F$ = Equivalent load on bearing	Ball Bearings: $k = 3$ Roller Bearings: $k = 3.33$
<b>BASIC STATIC LOAD</b>  $C_0$ = Required basic static load rating $SF_0$ = Factor of safety (See Table 10-11) $F_{MAX}$ = Maximum equivalent load on bearing	$C_0 = (SF_0)F_{MAX}$
<b>BEARING LOAD VS. LIFE</b>	$\frac{L_2}{L_1} = \left( \frac{F_1}{F_2} \right)^k$
<b>LIFE EXPECTANCY</b>  $h$ = Lifetime hours of operation $N$ = Speed in revolutions per minute For Variable Loads $R_1$ = Number of revolutions under Load 1 $L_1$ = Lifetime (revolutions) under Load 1 $R_T$ = Total revolutions expected from bearing	Conversion from lifetime in hours : $L = 60hN$  Variable loading: $L = \frac{1}{\frac{R_1}{R_T L_1} + \frac{R_2}{R_T L_2} + \dots}$
<b>BASIC DYNAMIC LOAD</b>  $L_{rated} = 10^6$ revolutions typically <u>Always verify rated life value</u> $K_S$ = Shock service factor (Table 10-12) These factors can be applied if the load rating is based on 90% reliability: $K_R = 0.62$ for 95% reliability $K_R = 0.33$ for 98% reliability $K_R = 0.21$ for 99% reliability	Dynamic load using rated (usually 90%) reliability: $C = F K_S \sqrt[k]{\frac{L}{L_{rated}}}$ (If $L = L_{rated}$ , $C = F K_S$ )  Dynamic load using adjusted (>90%) reliability: $C = F K_S \sqrt[k]{\frac{L}{K_R L_{rated}}}$

**Table 10-11: Static Load Safety Factors for Bearings**

Application Conditions	Rotating Bearings						Non-Rotating Bearings			
	Quiet Running Importance									
	Low		Normal		High					
Application Conditions	Ball Bearings	Roller Bearings	Ball Bearings	Roller Bearings	Ball Bearings	Roller Bearings	Ball Bearings	Roller Bearings		
Smooth, No Vibration	0.5	1	1	1.5	2	3	0.4	0.8		
Normal	0.5	1	1	1.5	2	3.5	0.5	1		
Significant Shock Loads	$\geq 1.5$	$\geq 2.5$	$\geq 1.5$	$\geq 3$	$\geq 2$	$\geq 4$	$\geq 1$	$\geq 2$		

**Table 10-12: Shock Service Factors for Bearings**

Application Conditions	Typical Range of $K_s$	
	Ball Bearing	Roller Bearing
Smooth, Uniform Load	1	1
Gearing	1.0 - 1.3	1
Light Impact	1.2 - 1.5	1.0 - 1.1
Moderate Impact	1.5 - 2.0	1.1 - 1.5
Heavy Impact	2.0 - 3.0	1.5 - 2.0

Loads used in life calculations are assumed to be constant and radial to the rolling elements. When calculating the required dynamic load rating for an application, the equivalent load (Table 10-9) on the bearing must be used rather than the applied loading. Load ratings in catalogs are usually based on an assumed bearing material and hardness. Typical assumptions are chromium steel bearing material and a hardness of 58 Rc. If alternative materials are required, load ratings may be affected.

The effects of friction and lubricant viscosity affect the operating temperature and life of the bearing. Bearing failure in the field is usually due to contamination, misalignment, and lubrication failure. As a result, actual life expectancy will be shorter than the rated value. A modified life calculation is available in standard ISO 281:1990/Amd 2:2000 to account for contamination and lubrication conditions. This method is quite complicated and is not presented here. Drag caused by seals can also be important in critical applications. The manufacturer can assist in calculating lubrication or seal drag.

## BEARING SELECTION PROCEDURE FOR A ROTATING SHAFT APPLICATION

Rotating shaft applications are the most common type of bearing selection situations. The best way to properly select and size a rolling element bearing is to speak with the manufacturer. Most bearing manufacturers have engineers on their staff ready to analyze your application thoroughly and make recommendations. When selecting a bearing for this type of application, the following procedure can be used:

1. Determine the design parameters. These include:
  - Expected lifetime of the bearing in hours or revolutions
  - Speed of the bearing
  - Bearing arrangement, defining the locating bearing(s)
  - Running load on the bearing, broken into axial and radial components
  - Expected shock load
  - Mounting and sealing requirements
  - Required precision
2. Select a bearing type based on performance or characteristics. Tables 10-3 and 10-4 can be useful when selecting a bearing type. One of the primary considerations will be whether radial, axial, or combined loading must be accommodated.
3. Select a bearing size from a catalog based on dynamic load rating. Calculate the equivalent load on the bearing using the equations in Table 10-9 and the manufacturer's catalog. Then calculate the required basic dynamic load needed for the application and required reliability level using the formulas in Table 10-10. Basic dynamic load rating ( $C$ ) is normally given in catalogs. Select a bearing with a dynamic load rating that exceeds the calculated dynamic load for the application by a factor of safety. A factor of safety for dynamic load as high as 5 is not out of the question.
4. Check the basic static load rating for the chosen bearing. Using an appropriate factor of safety (Table 10-11) and the equations in Tables 10-9 and 10-10, calculate the basic static load for the application and compare it to the basic static load rating for the chosen bearing. Basic static load rating ( $C_0$ ) is normally given in catalogs. Account for any peak loads including impact loads.

**532** Chapter 10

5. Check the limiting and rated operating speeds for the bearing. Speed in operation should never exceed the limiting speed of the bearing. Normal running speed should never exceed the rated operating speed.
6. Select bearing options such as seals, shields, lubricant, etc.
7. Select bearing accessories such as nuts, locking washers, spacers, wrenches, etc. The geometry for the shaft and housing should be finalized and all hardware accounted for on the bill of materials.



## CRITICAL CONSIDERATIONS: Rolling Element Bearings

- An appropriate factor of safety must be used when evaluating static and dynamic loading of bearings.
- Equivalent load, not applied load, must be used when selecting bearings based on static and dynamic load ratings.
- Most bearings have some “play” or internal clearance. If this is unacceptable, consider preloaded bearings or stiffer bearings (like needle roller bearings).
- Be sure not to axially constrain any bearing that cannot tolerate axial loading. This could cause the bearing to become overloaded if expansion occurs in the assembly due to the heat of running.
- Lubrication is essential to bearing life. Bearings used in oscillating applications may have reduced life due to inadequate lubricant distribution.
- Over-lubrication causes bearings to fail. Observe the manufacturer’s lubrication instructions. Calibrated grease guns, automatic lubrication systems, or ultrasonic monitoring can be used to prevent improper lubrication.
- Bearings should have a light press fit on the rotating race. If the fit is too loose, the bearing may rotate in/on its mount and cause wear and particulate contamination. If the fit is too tight, the bearing may be damaged, or internal clearance could be compromised. Tables 10-6 and 10-7 can be used to select proper fits on standard bearings.
- Tight geometric tolerancing is required on bearing support surfaces like bores, shafts, and seating surfaces. If the bearing is not fully and evenly supported, premature bearing wear and failure can occur. It is typical for manufacturers to specify these tolerances.
- Fine surface finishes are required on all bearing support surfaces. Rough surfaces can break down and cause fits to loosen.
- Care must always be used when installing bearings. Contamination and shock loading during installation must be avoided. Press bearings on with steady, even pressure around the entire race that is being fitted. Pressing forces should never be applied across the rolling elements in the bearing (i.e. never press on the inner race by applying force to the outer race, etc.).



## BEST PRACTICES: Rolling Element Bearings

- Consult the manufacturer for best results when designing a bearing application.
- Whenever possible, axial loading should be carried by thrust bearings. Use one thrust bearing per direction of axial load.
- The use of lubricated, sealed bearings simplifies the assembly design.
- Use standard precision class bearings (ABEC 1) for most applications.
- Design provisions for bearing dismounting if possible. Slots for bearing removal tools, grease fittings and channels for pressure dismounting, and holes for jacking screws are all useful.
- Use a reputable bearing distributor or manufacturer to avoid counterfeit components. Counterfeit bearings are a big business.
- Avoid using rolling element bearings in locations where heavy vibration occurs while the bearing is not rotating. This condition can cause deformation and wear in the bearing.
- Wave springs can be used to lightly bias a bearing in a housing or on a shaft with axial clearance.

## LINEAR BEARINGS

There are many types of linear bearings. Some examples are plain linear bushings, linear ball bushings, linear rails, and ball splines. Plain bearings are simple and cost effective, but are limited in speed and life by friction between the sliding elements. Ball or roller bearings replace sliding with rolling contact for higher speeds, load ratings, and life expectancies. Rollers tend to have higher load ratings than balls and are used in high load applications. For all linear bearings, life expectancy is measured in linear travel distance and is determined by component materials, hardness, lubrication, and load conditions.

Section   
**10.3**



## RECOMMENDED RESOURCES

- Consult a manufacturer for more information on linear bearings.

## LUBRICATION

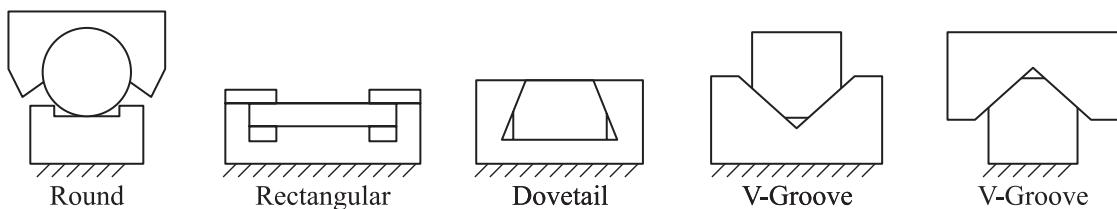
Plain linear bearings are generally used in a state of boundary lubrication. Grease or other thick lubricants are applied to the shaft and must be re-applied periodically to reduce friction and extend bearing life. Contaminants have easy access to linear plain bearings, so proper precautions or soft bearing materials must be used. For more information on boundary lubrication and plain bearing materials, see Section 10.1.

Rolling element linear bearings usually incorporate internal lubrication pathways into the bearing housing. Grease fittings are usually present on the bearing housing for lubrication purposes. These bearings often have contact seals at the shaft to reduce lubricant loss and prevent contaminants from entering the housing. Linear bearings should be lubricated periodically since some lubricant loss is to be expected.

## PLAIN LINEAR BEARINGS

Plain linear bearings are essentially the same as rotary plain bearings in design, materials, and static pressure ratings. See Section 10.1 for more information on these aspects of plain bearings. Linear plain bearings can take a variety of forms, including round sleeves, flat plates, and other shapes. In many cases, a linear plain bearing arrangement may be that of a slide and slideway; this arrangement allows movement along only one axis. It is not uncommon for both slide and slideway to be made out of hardened tool steel for long life and coated with dry film lubricants as well as thoroughly greased. Heavy loads may be carried with some configurations, and high precision achieved as long as wear is kept to a minimum. Heavy duty slide and slideways are found on machining centers, and light duty versions are commonly found on assembly machines and fixtures. Many versions are commercially available, but these are also easily designed in-house if needed. Some common slide and slideway configurations are shown in Figure 10-13, and some commercial plain bearing slide assemblies are shown in Figure 10-14.

Plain linear sleeve bearings are very common in industry. These bearings will allow rotation of the bearing on the shaft if torque is applied. It is important to prevent moment loading of the bearing because that will result in uneven wear and reduced life. Shafts for plain linear bearings are generally hardened and ground steel, and must be precisely aligned if used in parallel.



**Figure 10-13: Slide and Slideway Configurations**



**Figure 10-14: Commercial Plain Bearing Slide Assemblies**

Source: igus Inc. ([www.igus.com](http://www.igus.com))

Commercial linear plain bearings are normally selected based on PV factor, similarly to rotary plain bearings. However, linear plain bearings dissipate heat much more quickly than rotating bearings do. As a result, the PV factor rating for a linear plain bearing will normally be much

higher than its rotary counterpart. A plain bearing that is meant for linear movement should be clearly labeled as such in the manufacturer's catalog and should have a linear PV factor.

Boundary lubrication is the norm with linear plain bearings. Selection and sizing of linear plain bearings is performed similarly to selection and sizing of plain sleeve bearings for rotating service. See Section 10.1 for that procedure, using the formulas in Table 10-13 for PV calculation.

**Table 10-13: PV Formulas for Plain Linear Bearings**

PV FACTOR	PV factor = P x V
<b>INCH UNITS</b> $P$ = bearing pressure (psi) $F$ = load on the bearing (lbf) $A$ = bearing area ( $\text{in}^2$ ) $D$ = bearing internal diameter (in) or shaft external diameter $L$ = bearing length (in)	$P = \frac{F}{A}$ $A = DL$ $V = \text{bearing surface speed (ft/min)}$
<b>METRIC UNITS</b> $P$ = bearing pressure (MPa) $F$ = load on the bearing (N) $A$ = bearing area ( $\text{m}^2$ ) $D$ = bearing internal diameter (m) or shaft external diameter $L$ = bearing length (m)	$P = \frac{F}{A(10^6)}$ $A = DL$ $V = \text{bearing surface speed (m/min)}$

## ROLLING ELEMENT LINEAR BEARINGS

For rolling element linear bearings, rolling element bearing concepts and calculations discussed in Section 10.2 apply. When specifying linear bearings, the main criteria are bearing precision, internal clearance, static load rating, dynamic load rating, speed, and life expectancy. Equivalent load must be used when calculating dynamic load, and manufacturer's catalogs must be consulted in doing so. The life of linear bearings is often given in linear distance traveled. The ISO standard, which is commonly used by most manufacturers, is a dynamic loading life expectancy of 50 km. The formulas in Table 10-14 can be used to calculate dynamic load rating for linear bearings.

There are many types of rolling element linear bearings available commercially. The following are some common types and their descriptions.

**Table 10-14: Life and Load Ratings for Linear Bearings**

$L$ = life expectancy in linear distance $F$ = equivalent load on bearing	Ball Bearings: $k = 3$ Roller Bearings: $k = 3.33$
<b>BASIC STATIC LOAD</b> $C_0$ = required basic static load rating $SF_0$ = factor of safety (See Table 10-11) $F_{MAX}$ = maximum equivalent load on bearing	$C_0 = (SF_0)F_{MAX}$
<b>BEARING LOAD VS. LIFE</b>	$\frac{L_2}{L_1} = \left( \frac{F_1}{F_2} \right)^k$
<b>LIFE EXPECTANCY</b> $h$ = lifetime hours of operation $S$ = Stroke length $n$ = number of strokes per minute For Variable Loads $R_1$ = distance under Load 1 $L_1$ = lifetime (distance) under Load 1 $R_T$ = total distance expected from bearing	Conversion from lifetime in hours $L = 60h(2Sn)$ Variable loading: $L = \frac{1}{\frac{R_1}{R_T L_1} + \frac{R_2}{R_T L_2} + \dots}$
<b>BASIC DYNAMIC LOAD</b> $L_{rated}$ = 50 km typically <u>Always verify rated life value</u> $K_S$ = shock service factor (Table 10-12) These factors can be applied if the load rating is based on 90% reliability: $K_R = 0.62$ for 95% reliability $K_R = 0.33$ for 98% reliability $K_R = 0.21$ for 99% reliability	Dynamic load using rated reliability: $C = FK_S k \sqrt{\frac{L}{L_{rated}}}$ (If $L = L_{rated}$ , $C = FK_S$ ) Dynamic load using adjusted reliability: $C = FK_S k \sqrt{\frac{L}{K_R L_{rated}}}$

Ball bushings are very commonly used and consist of a sleeve containing ball bearings that ride on a smooth shaft. They are generally meant for light loading conditions. Some designs allow rotation of the bearing on the shaft (Figure 10-15), while most are not intended to rotate. In general, torque loading must be avoided. Ball bushings are often used in pairs, running on parallel shafts. Ball bearings in the sleeve are usually re-circulated to provide continuous rolling contact with the shaft. Ball bushings are available in both closed and open configurations, with and without lubrication-preserving end caps. Some examples of these are shown in Figures 10-16 and 10-17. A closed sleeve is used with end supported shafts while an open sleeve is used with continuously supported shafts. Preloaded ball bushings are commercially available. Ball bushings have a limited capacity to carry moment loads (about an axis perpendicular to the bushing/shaft axis). Moment load ratings are often given for ball bushings, and using them in pairs is a common solution to eliminate moment loading. Longer bushings generally have greater moment load capacities.



**Figure 10-15: Rotary Linear Ball Bushings**

Source: Misumi USA Inc. ([www.misumiusa.com](http://www.misumiusa.com))

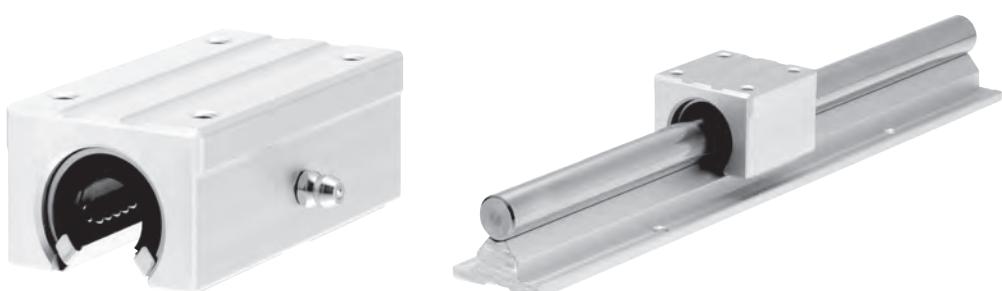


With End Caps

Without End Caps

**Figure 10-16: Ball Bushings**

Source: Misumi USA Inc. ([www.misumiusa.com](http://www.misumiusa.com))



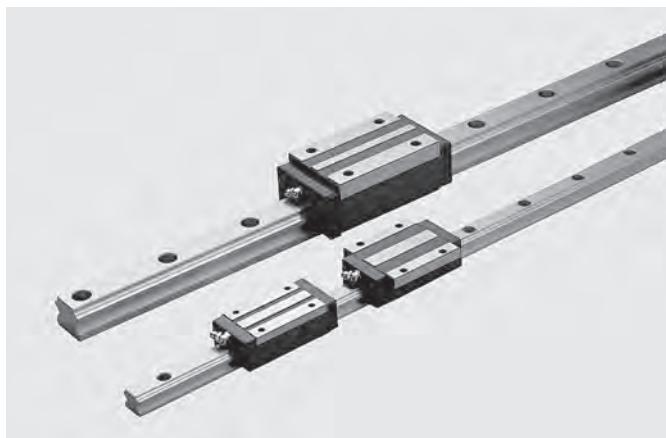
**Figure 10-17: Open Ball Bushings**

Source: Misumi USA Inc. ([www.misumiusa.com](http://www.misumiusa.com))

**Figure 10-18: Ball Splines**Source: Misumi USA Inc. ([www.misumiusa.com](http://www.misumiusa.com))

Ball splines (Figure 10-18) are recommended when the assembly must resist rotation of the bearing on the shaft under torsional loading. Engagement of the ball bearings within the sleeve with axial splines on the shaft prevents rotation. Ball splines are often rated in terms of allowable torque load, and are generally designed to transmit torque while allowing linear movement. Ball splines have a limited capacity to carry moment loads (about an axis perpendicular to the bushing/shaft axis). Moment load ratings are often given for ball splines, and using them in pairs is a common solution to eliminate moment loading. In general, longer spline nuts can carry greater moment loads.

Linear rails and guides (Figure 10-19) are a compact solution to the problem of preventing rotation while allowing linear movement. These assemblies normally consist of a rectangular rail and a bearing carriage that rides along the rail. In general, the carriage or guide is captive to the rail and can support loads in every

**Figure 10-19: Linear Rail and Guide Assemblies**Source: SBC Linear Co., Ltd. ([sbclinear.co.kr/eng/index.php](http://sbclinear.co.kr/eng/index.php)) Courtesy of TPA ([www.tpa-us.com](http://www.tpa-us.com))

direction. Consult the manufacturer for specific load carrying capabilities because these vary between models. These assemblies can generally carry moment loads as well, though this must be verified for each model. If large moment loads are present, the use of two guides on one rail, or two rails side by side should be considered. Both ball and roller versions are available commercially.

Crossed roller ways (Figures 10-20 and 10-21) are highly compact and rigid assemblies consisting of two angled rows of rollers between two linear races. They are capable of carrying very heavy loads. These assemblies can withstand significant moment loads and are often used as table bearings in machine tools. The rollers do not re-circulate, so movement is generally smoother than that of recirculating ball bushings. Due to their configuration, crossed roller ways must be twice as long as their expected stroke.



Extended Load Capacity



Needle Rollers



Curved Crossed Roller Way

**Figure 10-20: Crossed Roller Ways**

Source: PM Bearings ([www.pmbearings.nl](http://www.pmbearings.nl)) Courtesy of TPA ([www.tpa-us.com](http://www.tpa-us.com))



**Figure 10-21: Crossed Roller Slide Assemblies**

Source: PM Bearings ([www.pmbearings.nl](http://www.pmbearings.nl)) Courtesy of TPA ([www.tpa-us.com](http://www.tpa-us.com))

Selection and sizing of linear rolling element bearings is performed in a similar way to the sizing and selection of rotating bearings. See Section 10.2 for that procedure, and use the formulas in Table 10-14 to calculate dynamic load ratings for linear bearings.



### CRITICAL CONSIDERATIONS: Linear Bearings

- Use an appropriate factor of safety when performing bearing calculations.
- Proper alignment is critical to linear bearing function and life. When two linear bearings are used in parallel, overconstraint must be avoided.
- Lubrication is essential to long bearing life, and contamination of bearings must be avoided.



### BEST PRACTICES: Linear Bearings

- Consult the manufacturer for best results when selecting and sizing linear bearings.
- Avoid applying moment loads to linear bearings.
- Prevent contamination of linear bearings as much as possible.

# INDEX

## A

ABEC 520–523  
 AC motors (see also: motors) 484  
     altitude 486  
     AMB 483  
     asynchronous 484, 491  
     bearings 488  
     capacitor correction 488  
     CONT 484  
     cooling 484, 494  
     current, locked rotor 486, 488  
     design code 486  
     duty or time rating 484  
     efficiency 486  
     ENCL (enclosure type) 484  
     FLA (full-load amps) 484  
     frame size 484, 493  
     kVA code 486  
     locked rotor current 486, 488  
     MAX CORR KVAR 488  
     nameplate 483, 484  
     OVER TEMP 486  
     performance 489, 495  
     phases 484  
     power factor 488  
     rated frequency 484  
     rated load current (FLA) 484  
     rated torque 488  
     rated voltage 486  
     service factor 486  
     shaft 488, 493  
     speed control 491  
     synchronous 484, 487  
     synchronous speed 484, 486, 497  
     TEFC 494  
     TENV 494  
     thermal 483, 486, 491, 495  
     torque 483, 486, 494  
     torque, accelerating 488  
     torque, breakaway 488  
     torque, breakdown 488  
     torque, full-load 488  
     torque, peak 488  
     torque, pull-in 489  
     torque, pull-out 489  
     torque, pull-up 489  
     torque, rated 488  
     torque, starting 488  
     torque, static or locked rotor 488

types and characteristics 487  
     undervoltage 483  
 AC power 482–484  
 acceleration  
     gravitational 16, 18  
     linear motion 31  
     rotary motion 32  
 access, workspace 39, 44, 45, 80, 82, 87, 89  
 acetal 388  
 ACME screw 667, 672, 673  
 active coils (see: springs)  
 addendum 576, 581, 601, 608–610  
 adjustability, assembly 11, 133  
 AGMA 574, 575, 589, 590–593, 595, 596, 598  
 air actuator (see: pneumatics, actuator)  
 air cylinder (see: pneumatics, actuator)  
 AISI 371  
 alloy steel 380, 385, 371, 372, 378, 406, 418, 548  
 Alumina 378  
 aluminum (see: materials)  
 AMB 483  
 analysis  
     design 1, 10  
     risk 48, 49, 73, 685  
 angle, pressure 576, 577, 579–581, 610  
 angular contact ball bearings 515, 519, 520  
 angular misalignment 514, 516, 517, 566, 567, 569, 571  
 angularity 122, 173  
 annealing 401  
 anodizing 409  
 anthropometry (see: body dimensions)  
 area moments of inertia 21  
 areas and perimeters 20  
 assemblability 187  
 availability 684, 697  
 available time 684, 697  
 AWS 359, 361  
 axial stress 27, 561

## B

backdrive 666–668, 673  
 backlash  
     couplings 563, 567–570, 573

gearboxes (see: gearboxes)  
 gears 576, 580, 589, 591–595, 599, 601  
 linear motion screws 666, 672, 673  
 ball bushings 538, 539, 541  
 ball screw (see also: linear motion screws) 664, 665  
     backdrive 666–668  
     backlash 666  
     calculations 667, 670, 671, 676  
     design relationships 677  
     dynamic load rating 674–676  
     efficiency 666–668, 672, 674  
     failure 674  
     life 672, 675–677  
     loading 664, 666–670, 674–676  
     preload 672, 677  
     selection and sizing 675  
     speed 671  
     static load rating 677  
     torque 667, 668  
 ball splines 540  
 basic dimensions 119, 120  
 beam coupling 567, 568, 573  
 beam deflection and forces 23, 24  
 bearing stress 27, 223  
 bearings 501  
     clearance 506, 507, 512, 513, 521, 525  
     gearbox 616, 622  
     linear (see: linear bearings)  
     motor 488  
     plain (see: plain bearings)  
     rolling element (see: rolling bearings)  
     shaft 547, 549, 553, 554  
 Belleville springs (see also: springs) 416, 456  
     allowable stress 461  
     assembly considerations 459  
     catalog selection steps 459  
     deflection stable range 459  
     deflection vs. force 457, 458  
     design steps 463  
     diameter ratio 460  
     force vs. deflection 457, 458  
     geometry 457  
     height and thickness 457  
     materials 418, 461  
     parallel 457, 458, 461

**702 Index**

series 457, 458, 461  
 sizing equations 460  
 snap action 459  
 stable range of deflection 459  
 stack instability 458  
 stacking 457, 458  
 stress 459, 461  
 yielding safety factor 461  
 bellows coupling 467, 571, 573  
 belts (see also: belts and chain) 627, 629  
   drive shafts 627, 637  
   forces on shafts 633, 634, 638, 650  
   angle of wrap 629, 649  
   best practices 653, 654  
   critical considerations 652  
   flat (see: flat belt)  
   friction drive 629, 653  
   speed recommendations 629, 630  
   timing or synchronous (see: timing belt)  
   v-belt (see: v-belt)  
 belts and chain (see also: belts) 627  
   (see also: chain)  
   center distance 629  
   drive calculations 627–629  
   length 629  
   pitch diameter 628  
   resources 627  
   speed ratio 628  
 bending stress 548, 555, 600  
 best practices  
   belts 653, 654  
   chain 663  
   couplings 573  
   design 11, 12, 14  
   fasteners 299  
   fits 116  
   gearboxes 626  
   gears 612, 613  
   heat treatment 407  
   keys 227  
   lead, ball, and roller screws 680  
   limits 116  
   limits, fits, and tolerance grades 116  
   linear bearings 542  
   locating techniques 212  
   machine reliability and performance 699  
   materials 391  
   motors 499  
   pins, keys, and retaining rings 227  
   pipe and port threads 282  
   plain bearings 510

pneumatics 481  
 precision locating 212  
 retaining rings 227  
 rolling bearings 534  
 shafts 562  
 springs 465, 466  
 surface finish 398  
 surface treatment 412  
 threaded fasteners 299  
 threaded inserts 308  
 tolerance grades 116  
 tolerance stack-ups 177  
 tolerances on drawings and GD&T 127  
 washers 299  
 welds and weldments 368  
 bevel gear (see also: gears) 582, 607, 585, 586  
   backlash 591, 592, 594  
   equations 609, 610  
   miter gears 607  
   lubrication 598  
   mounting 594  
   terminology 608–610  
 Bisque Alumina 378  
 black oxide 408, 294, 366  
 body  
   capabilities and limitations 37, 38, 41, 42  
   dimensions 39, 41, 42, 73, 79, 80, 86, 87  
 bolt  
   preload 295, 297, 298  
   stripping 295  
   torque 298–301  
 boundary 161, 162  
   calculations 163  
   example problem: spring pin 164  
   LMB 162  
   MMB 161  
 Brinell 399  
 brittle materials 13  
 brown-out 483  
 buckling  
   air actuator rod 473  
   linear motion screws 669, 670  
   springs 427, 430, 431  
   column 25  
 bushings (see: plain bearings)  
 butt joint 360  
 button head cap screws (see: screws)

**C**

calculation (see: equations)  
 calipers 9  
 cap screws (see: screws, hex head cap)  
 capability (see: process capability)  
 carbon steel 372, 373, 380, 402  
 carburizing 402, 405, 406  
 Cardan joint 565  
 case hardening 373, 379, 401–403, 405  
 center distance  
   belts and chain 629  
   gear 578, 591–594  
 ceramics 376, 378  
 chain (see also: belts and chain) 627, 655  
   angle of wrap 629  
   attachments 656, 657  
   best practices 663  
   calculations 628, 629, 660  
   critical considerations 662  
   dimensions 656  
   drive calculations 628, 629  
   forces on shafts 660  
   length 660  
   lubrication 655  
   pitch 656  
   pitch diameter 660  
   power 658, 660  
   roller 655  
   selection and sizing 658  
   service factor 661  
   shaft 661  
   shaft loading 660  
   speed 660  
   sprocket 655, 656, 661  
   standards 656  
   tolerance stack-up 129  
 check valves 476, 479  
 chrome plating 408–411  
 circular pitch 576, 579, 600, 601, 609  
 circular runout 123, 124, 174  
 circularity 121, 168, 174  
 clearance 129, 146, 158, 159, 163, 181, 188, 192, 200, 217, 220  
   bearing 506, 507, 512, 513, 521, 525  
   gear 576, 591, 621  
   linear motion screws 666  
   retaining rings 268, 270, 272, 274, 276, 277  
   springs 431  
   screws 302–304, 310, 312, 314, 316, 330, 332, 334, 336, 338, 340

- tap drills 288  
 workspace 39, 43, 87  
 wrench 301, 304, 338, 340,  
 342–345  
 clearance fit (see also: fits) 95, 99, 183,  
 186, 189, 223  
 criterion 193, 196, 204, 205,  
 209, 211  
 keys 223  
 clevis pins 222  
   data, inch 252, 253  
   data, metric 254, 255  
 closed center circuit 467  
 coating (see: surface treatment)  
 codes and regulations, machine safety 71,  
 72, 85–91  
 coefficient of friction  
   linear motion screws 668  
   bolt tightening 299–301  
 coefficient of thermal expansion 18, 375,  
 376, 379, 384–387  
 coil springs (see: springs)  
 coil stress (see: springs)  
 coiled spring pins (see: spring pins)  
 cold work tool steel 381, 383, 385  
 column buckling 25, 473, 669, 670  
 combined tolerance stack-up 143, 144  
 composite tolerance 160, 173, 196,  
 197, 199  
 compound tolerance frames 126  
 compressed air 52, 67, 466, 467  
 compression ratio, pneumatic  
 actuator 475  
 compression springs (see also: springs)  
   Belleville washers (see: Belleville)  
   helical coil (see: helical coil)  
   compression  
   types 415–418  
 compressive strength 374  
 concentricity 123  
 conceptual design 9  
 condition monitoring 698  
 conductivity, thermal 376  
 cone point set screw (see: screws, hex  
 socket set, cone point)  
 conjugate action 577, 578  
 conversion, units 15, 17, 18  
 conveyor, forces on shafts 618, 550, 551  
 corner joint 360  
 corrosion resistance 375, 378, 379, 407–410  
 cost  
   scrap 696, 697  
   unit 696, 697  
 cotter pins 223  
   data, inch 256, 257  
   data, metric 258, 259  
 countersunk head cap screws (see:  
 screws, hex socket flat countersunk head  
 cap screws)  
 couplings 563  
   attachment 563  
   backlash 563, 570, 573  
   beam 567, 573  
   bellows 567, 573  
   best practices 573  
   Cardan joint 565  
   clamping 563, 565  
   critical considerations 573  
   disc 568, 573  
   flexible 567  
   high torque 563, 565  
   inertia 571  
   jaw 569, 573  
   keys 563  
   moment of inertia 571  
   Oldham 569, 573  
   phase misalignment 564  
   resources 563  
   rigid 564, 565  
   selection 570  
   set screws 563  
   shaft loading 570  
   shaft misalignment 564, 573  
   slit 567, 573  
   speed 564, 571  
   stress risers 563  
   torque 563, 571  
   types 564  
   u-joint 565  
   zero backlash 571, 573  
 $C_{pk}$  (see: process capability index)  
 critical buckling, columns 25, 473, 670  
 critical considerations  
   belts 652  
   chain 662  
   couplings 573  
   design 14  
   ergonomics 46  
   fasteners 298  
   fits 116  
   gearboxes 626  
   gears 612  
   heat treatment 406  
   keys 226  
   lead, ball, and roller screws 680  
   limits 116  
 limits, fits, and tolerance grades 116  
 linear bearings 542  
 linear motion screws 680  
 locating techniques 212  
 machine reliability &  
 performance 698  
 machine safeguarding 65  
 machine safety - design process 51  
 materials 390  
 motors 499  
 pins, keys, and retaining rings 226  
 pipe and port threads 282  
 plain bearings 510  
 pneumatics 480, 481  
 precision locating 212  
 retaining rings 226  
 rolling bearings 533  
 safety issues – other 71  
 shafts 562  
 springs 465  
 surface finish 398  
 surface treatment 412  
 threaded fasteners 298  
 tolerance grades 116  
 tolerance stack-up 176  
 tolerances on drawings and  
 GD&T 126  
 washers 298  
 welds and weldments 367  
 critical speeds  
   linear motion screws 670, 671  
   shafts 26, 556, 559  
 criticality 49, 685–687, 689, 691  
 criticality matrix 688, 689  
 crossed helical gear (see: helical gear)  
 crossed roller ways 541, 542  
 cup point set screw (see: screws, hex  
 socket set, cup point)  
 $C_v$  472, 474, 475, 480  
 cylindrical roller bearings 512, 516,  
 519, 520  
 cylindrical roller thrust bearings 518, 520  
 cylindricity 122

**D**

- danger signals 69, 81, 89, 90  
 datum 118, 119, 148–151, 162, 165,  
 166, 168  
 datum reference frame 185, 186, 147,  
 148, 155, 166, 169, 170, 171, 174, 198  
 datum shift 168–171

# 704 Index

- DC motors (see also: motors) 489  
 armature rated load current 490  
 base speed 490  
 brush 489  
 maximum speed 490  
 nameplate 483, 490  
 power supply 490  
 rated armature voltage 490  
 rated field voltage 490  
 speed control 491  
 terminology 490  
 types and characteristics 489, 491  
 winding type 490
- DC power 482
- decision matrix 9
- dedendum 576, 601, 608, 609
- deep groove ball bearings 514, 519, 520
- deflection  
 beams 23, 24  
 Belleville springs 456–461  
 helical coil compression springs 423, 426–428, 431, 432  
 helical coil extension springs 423, 441–444  
 helical coil torsion springs 423, 450–452  
 linear motion screws 669, 670  
 shafts 549, 553–555, 560
- DELPHI technique 50
- Delrin 376, 377, 388
- design  
 analysis 1, 10  
 assemblability 187–189, 214  
 assemblies and systems 11  
 best practices 14, 15  
 conceptual 9  
 critical considerations 14  
 detail 10  
 functional specification 3  
 interchangeability 133, 187, 214  
 locating techniques 181, 187, 191  
 machinery 3  
 parts 12  
 research 8  
 resources 3, 8  
 safety 13, 37, 38  
 shafts 558  
 specification 3, 9  
 springs, Belleville 463  
 springs, compression 437  
 springs, extension 447  
 springs, torsion 454  
 synthesis 9
- weldments 359, 368, 592
- detail design 10  
 assemblies and systems 11  
 parts 12
- deviations (see: tolerance)  
 diametral pitch, gear 579, 580  
 diamond pin (see: pins)
- dimensions  
 body 39–42, 73, 75, 79, 80, 86–88  
 workspace 39, 40, 43–45
- dimensions and tolerances 93
- disc coupling 568, 573
- distortion 366, 381, 391, 402, 403
- distribution, normal 137–139
- dog point set screw (see: screws, set, hex socket dog point)
- double acting (see: pneumatics, actuator)
- dowel pins 220, 219, 191, 98, 182
- data, inch 228, 229, 195, 203  
 data, metric 230, 231, 194, 202  
 pullout (see: dowel, withdrawal)  
 precision locating dimensions 194, 195, 202, 203  
 stress and materials 217, 218  
 withdrawal 220  
 withdrawal, data, inch 232, 233  
 withdrawal, data, metric 234, 235
- downtime 684, 685, 697, 698
- drawings  
 best practices 127  
 critical considerations 126  
 GD&T 116  
 tolerances 116  
 weldments 364  
 ductility 375, 380, 399
- E**
- E (modulus of elasticity) 375, 385, 387, 418, 419, 461  
 edge joint 360  
 efficiency (see also: machine efficiency)  
 gearboxes 614, 615, 620, 621  
 linear motion screws 666–668, 671–674  
 electric motors (see: motors)  
 electrical power 482  
 electroless nickel plating 366, 409–411  
 electroplating 408  
 electropolishing 408, 410, 411, 398  
 emergency stop devices 70, 71, 81, 90
- enclosures  
 controls for motors 493  
 motors 484, 493, 494  
 workspace 39
- endurance  
 bolts 297  
 springs 424, 425  
 strength 19
- engineering units 15
- epicyclic gear trains 588, 589
- equations, general 18  
 area moments of inertia 21  
 areas and perimeters 20  
 beam deflection and forces 23, 24  
 buckling of columns 25  
 column buckling 25  
 critical speed of shafts 26  
 Euler's formula for buckling 25  
 intermediate column buckling 25  
 lifting, NIOSH 46  
 mass moments of inertia 22  
 moments of inertia, area 21  
 moments of inertia, mass 22  
 perimeters and areas 20  
 resources 18  
 right triangle relationships 19  
 surface areas and volumes 21  
 useful values and equations 18  
 volumes and surface areas 21
- equipment (see: machine)
- ergonomics  
 access openings 39, 44, 45, 80  
 books 74, 75  
 capabilities and limitations 37, 38, 41–43, 86  
 clearances 39, 87  
 codes 72, 73  
 critical considerations 46  
 enclosures 39  
 forces 38, 42, 79, 86, 89  
 lifting 41, 43, 46, 68  
 machine safety 37, 38  
 regulations 72, 73  
 standards 40, 46, 79, 80, 83  
 web sites 84, 85
- e-ring (see: retaining rings)
- Euler's formula for buckling  
 columns 25  
 pneumatics 473  
 power screws 670
- exact constraint design 11, 181, 186
- explosive atmospheres 68, 82
- extension springs (see also: springs)

helical coil (see: helical coil extension)  
types 416–418  
external retaining rings (see: retaining rings)  
Eytelwein's equation 632, 636

**F**

face of weld 360  
factors of safety 13, 375, 441  
common values 14  
fatigue 29, 295, 297, 423–425  
failsafe 71, 693  
failure  
modes (see: FMECA)  
MTBF 684  
MTTF 684  
prediction 698  
rate 684, 685  
failure modes, effects, and criticality analysis (see: FMECA)  
fastener (see also: bolt)  
(see also: nuts)  
(see also: screws)  
best practices 299  
critical considerations 298  
engagement length 287, 295, 308  
grades 295  
materials 294  
resources 285  
selection criteria 294  
strength 295–297  
stripping 295  
torque 298–301  
types 294, 301  
fastener threads 286–288  
tap drills 288–293  
fatigue  
bolts 295, 297  
equations 28, 29  
helical coil springs 423–426  
shafts 548, 549, 555, 556, 561  
weldments 359  
fault tree analysis 49  
feather keys (see: keys, parallel)  
feature control frame 119, 120  
feeler gauge 13  
fender washers (see: washers, wide)  
fillet weld 360  
finished hex bolts (see: screws, hex head cap)

fits 95  
ANSI 96, 100  
bearings 521–523  
best practices 116  
class 95, 96  
clearance 95  
commonly used 99  
critical considerations 116  
force 98  
grades 96, 97, 100, 101  
interference 95  
ISO 96, 97  
IT grades 101  
limits 95, 100, 101  
preferred 96  
tolerance grade 95–97, 100, 101  
transition 95  
types 95  
fixed fastener 161, 183, 184  
fixture, assembly 133  
flame hardening 401, 402, 405, 375  
flat belt (see also: belts) 629  
bending frequency 633  
calculations 628, 629, 632, 633  
pitch diameter 630  
power 632  
selection and sizing 632  
service factor 633  
shaft loading 551, 618, 633  
shafts 636, 637  
slip 629, 630, 632  
speeds 629, 634  
tension 629, 632, 633  
torque 632  
width 635  
flat head cap screws (see: screws, hex socket flat countersunk head cap screws)  
flat point set screw (see: screws, hex socket set, flat point)  
flat washer (see: washers)  
flatness 121  
flexible couplings 567  
floating fastener 161, 183–185  
FMEA (see: FMECA)  
FMECA 10, 683, 685  
procedure 692  
RPN 690, 691  
worksheet 686–688, 690  
foot-pound-second system 16  
force gauge 9  
four-point contact ball bearings 515, 516  
FPS (foot-pound-second system) 16

friction  
coefficient 299–301  
lead screws 668  
plain bearings 503–507  
functional datums 118, 185  
functional design specification (see: design, specification)  
fusion zone 360

**G**

G (modulus of rigidity) 375, 385, 387, 419  
gauge  
feeler or thickness 13  
force 9  
setup 11, 209  
sheet metal 389  
GD&T 116, 117  
angularity 122  
basic dimensions 119, 120  
best practices 127  
circular runout 123, 124  
circularity 121  
compound tolerance frames 126, 198, 199  
concentricity 123  
critical considerations 126  
cylindricity 122  
datums 118, 148  
feature control frame 119, 120  
flatness 121  
LMC 126, 154  
MMC 126, 152  
modifier 126, 148  
parallelism 122, 123  
perpendicularity 122, 123  
position 125  
profile of a surface 124  
resources 116  
RFS 126  
runout, circular 123, 124  
runout, total 124  
standards 119, 120  
straightness 120  
symbols 119, 120  
total runout 124  
gearboxes 614  
backlash 621  
bearings 616, 620, 622  
best practices 626  
calculations 617, 618, 625

**706** Index

- configurations 614, 615, 619  
 critical considerations 626  
 direction of rotation 619  
 efficiency 614, 615, 620, 621  
 forces on 616–618  
 gear types 614  
 inertia 616–618, 625  
 in-line 614, 615  
 intermittent motion 620  
 lateral loads 616, 622  
 life 620, 622  
 loads on 616–618  
 lubrication 615, 619, 622  
 motors 621, 623  
 mounting 621  
 noise 620, 621, 623  
 overhanging moment rating 622  
 power 614, 621, 625  
 protection class 623  
 radial load rating 622  
 ratio 615, 620, 621  
 right angle 614, 615  
 rigidity 619, 621  
 RMC torque 620, 625  
 selection and sizing 619, 623  
 service factor 619  
 service life 622  
 shaft types 622  
 speed 620  
 stages 615  
 temperature 619, 623  
 thrust loads 616  
 torque 614–620, 625  
 torsional rigidity 619, 621  
 transmission error 620, 621
- gears** 574  
 attachment 589  
 backlash 576, 580, 589, 591–595, 599, 601  
 best practices 612, 613  
 bevel (see: bevel gear)  
 critical considerations 612  
 custom 581, 604, 605  
 forces on shafts 551, 552, 606, 608–610, 617  
 gearboxes (see: gearboxes)  
 helical (see: helical gear)  
 idler 587  
 law of gearing 577  
 lubrication 596, 598  
 materials 595, 597, 603  
 pitch line speed 591, 596, 598, 599, 602  
 quality ratings 589–591
- rack and pinion (see: rack and pinion)  
 ratio 576, 578, 582, 587, 588, 592, 600  
 resources 574  
 service factor 603  
 shafts 589  
 speed, pitch line 591, 596, 598, 599, 602  
 speed ratio 576, 578, 582, 587, 588, 592, 600  
 spur (see: spur gear)  
 stress 603  
 standards 574–576  
 surface treatments 595  
 tooth thickness 592, 601, 609  
 torque ratio 582  
 types 582–586  
 velocity ratio 576, 578, 582, 587, 588, 592, 600  
 wear 595, 596, 598, 599, 601
- worm** (see: worm gear)
- gear trains**  
 compound 588  
 epicyclic (planetary) 588, 589  
 ratio 582, 587, 588  
 simple 582, 587  
 single stage 582, 587  
 two-stage 588
- Geometric Dimensioning and Tolerancing** (see: GD&T)
- Goodman diagram** 423–425
- grades**  
 fits 95–97, 100–102  
 threaded fasteners 295
- grasping** 41–43, 46
- groove weld** 360
- grooved pins** 221, 222, 217, 440  
 data, inch 248, 249  
 data, metric 250, 251
- guard** (see: machine safeguarding)
- H**
- half dog point set screw (see: screws, hex socket set, half dog point)  
**hardenability** 380, 381, 406  
**hardening** (see also: heat treatment)  
 strain 401  
**hardness** (see also: heat treatment)  
 375, 399  
 achieving 398  
 case hardening properties 405
- common values 401  
 materials 384, 386, 387  
 on drawings 399  
 ranges achievable 381, 382, 404  
 scales 399, 400  
 shafts 507, 509, 549  
 shear 400  
 surface treatment 408, 409  
 tensile strength 375, 399  
 wear resistance 375, 382
- hardware** (see also: fasteners)  
 (see also: washers)  
 pins, keys, and retaining rings 215  
 pipe threads, threaded fasteners, and washers 279
- hardware tables** 188
- hardware, locating** (see: pins)
- HAZ** 360
- hazard** (see: risk)
- heat**  
 expansion (see: thermal expansion)  
 safety 66
- heat affected zone** 360, 365
- heat treatment** (see also: hardness) 398  
 best practices 407  
 critical considerations 406  
 distortion 403, 402, 406  
 processes 401, 402  
 resources 399
- helical coil compression springs** (see also: springs)  
 active coils 422, 431, 432  
 allowable stress 427, 433  
 buckling 427, 430, 431  
 captivation in assembly 427, 429  
 catalog selection steps 429  
 clearance around 427, 431  
 deflection 422, 423, 426–428, 431, 432  
 design steps 437  
 end types 427, 428  
 fatigue 423–426, 433  
 force vs. deflection 426–428, 432  
 geometry equations 432  
 length 426, 427, 431, 432  
 linear range 423, 426  
 natural frequency (surge) 423, 432  
 parallel 426, 427, 432  
 series 426, 427, 432  
 sizing equations 431  
 solid height 426, 431, 432  
 spring constant 422, 432  
 spring index 422, 431  
 spring surge 423

stability 430  
 static service 426, 433  
 stress 432, 433, 422–424, 427, 429  
 wire diameter 421, 422, 431  
 helical coil extension springs (see also: springs)  
     active coils 422, 443  
     allowable stress 423–425, 441, 446  
     captivation in assembly 440  
     catalog selection steps 443  
     deflection 422, 423, 441–444  
     design 447  
     ends 440–442  
     fatigue 423–426  
     geometry 441, 442, 442  
     hooks 440–443  
     initial tension 441, 444  
     length 440, 441, 443  
     loops 440–443  
     natural frequency 423, 444  
     overload 441  
     parallel 441, 442, 444  
     series 441, 442, 444  
     shock loading 441  
     spring constant 422, 444  
     spring index 422, 443  
     spring sizing equations 443  
     spring surge 423  
     stress 423, 424, 426, 441, 442, 444, 446  
     wire diameter 421, 422, 443  
 helical coil threaded inserts (see: threaded inserts)  
 helical gear (see also: gears) 584, 606  
     backlash 593  
     equations 607  
     helix angle 606  
     loads on shafts 551, 606  
     lubrication 596, 598  
     materials 595  
 helix angle 606  
 hex head cap screws (see: screws, hex socket head cap)  
 hex lock nuts (see: nuts, prevailing torque hex lock nuts)  
 hex socket button head cap screws (see: screws, hex socket button head)  
 hex socket flat countersunk head cap screws (see: screws, hex socket flat)  
 high collar lock washers (see: washers, high collar lock washers)  
 high speed tool steel 381, 383, 385  
 holes  
     depth, tap drills 288, 293

processes, tolerances, costs 190  
 tap drills 288–293  
 hollow shafts (see: shafts)  
 hook stress (see: extension springs)  
 hoop tension 633, 638  
 horsepower 33  
     belts and chain 632, 637, 640, 644, 649, 658, 660  
     motors 483, 497  
     shafts 550  
     gear 602  
 hot work tool steel 381, 383, 385  
 HP (see: horsepower)  
 human factors (see: ergonomics)  
 hypoid bevel gear 586

**I**

IB 161, 162, 163  
 idler 587  
 Imperial units 15  
 implied tolerance 117  
 inch-pound-second system 16  
 induction hardening 402, 405  
 inertia  
     couplings (see: couplings)  
     gearboxes (see: gearboxes)  
     motors (see: motors)  
     ratio 497  
 initial tension  
     bolts 295, 297  
     springs 441, 444  
 inner boundary 161, 162, 163  
 inserts, threaded (see: threaded inserts)  
 interchangeability 133, 187, 214  
 interference, gear 580, 581, 592  
 interference fit (see: fits)  
 intermediate column buckling 25, 670  
 internal retaining rings (see: retaining rings)  
 involute 578, 579  
 IPS (inch-pound-second system) 16  
 IT tolerance grades 97, 101

**J**

jam nuts (see: nuts, thin)  
 jaw coupling 569, 573  
 joints, welded 360  
 journal 504, 505

**K**

keys 223  
     bearing stress 217, 218  
     best practices 227  
     critical considerations 226  
     feather 223, 224  
     length 223  
     materials 217, 218  
     parallel 223, 224  
     parallel, data, inch 260, 261  
     parallel, data, metric 262, 263  
     resources 217  
     shafts 219, 223, 224, 547, 548, 563, 589  
     shear 217, 218  
     stress 218  
     surface finish 396  
     tapered 224  
     Woodruff 224  
     Woodruff, data, inch 264, 265  
     Woodruff, data, metric 266  
 kinematic fixturing 186  
 $K_v$  474

**L**

lap joint 360  
 laser 66  
 lay (see: surface finish)  
 lead screw (see also: linear motion screws) 665, 671–673  
     ACME thread 673  
     backdrive 666, 673  
     buttress 673  
     design or dynamic load 673  
     efficiency 667, 668, 673  
     forces on shafts 617, 667–669  
     friction 668  
     plastic nut 674  
     power 667, 668  
     preload 673  
     PV 674  
     selection and sizing 675  
     speed 671, 674  
     static load rating 677  
     torque 667, 668  
 least material boundary (see: LMB)  
 least material condition (see: LMC)  
 leg of weld 360  
 Lewis formula with Barth revision 600, 602  
 lifting 38, 41, 46, 67

## 708 Index

- limits (see also: fits) 95, 96  
 best practices 116  
 commonly used 99  
 critical considerations 116  
 of size 95, 97, 104–115  
 linear bearings 534  
     ball bushings 538, 539  
     ball splines 540  
     best practices 542  
     critical considerations 542  
     crossed roller ways 541  
     loads 537, 538  
     lubrication 535  
     plain bearings 535, 536  
     plain, boundary lubrication 537  
     plain, PV 536, 537  
     plain, sleeve 535  
     rails and guides 540  
     resources 534  
     rolling element 537  
     rolling element, life & loads 538  
     slide configurations 536  
     speed 534, 532  
     torque 535, 538, 540  
 linear motion equations 31  
 linear motion screws 664  
     accuracy or error 666  
     backdrive 666, 667  
     backlash 666  
     ball (see: ball screw)  
     best practices 680  
     buckling 669, 670  
     calculations 667, 670, 671  
     characteristics 664  
     critical considerations 680  
     critical speeds 670, 671  
     deflection 669, 670  
     efficiency 666–668, 671–674  
     Euler's formula for buckling 670  
     geometry 668, 669  
     lead 666  
     lead (see: lead screw)  
     number of starts 666  
     pitch 664  
     power 667  
     resources 664  
     roller 672  
     root diameter 666  
     selection 675  
     speeds, critical 670, 671  
     stress 669, 670  
     torque 667, 668  
 linear rails and guides 540  
     LMB 161–163  
     LMC 126, 152, 154, 163, 164  
     loads on bolts 295–298  
     locating pins, stepped (see: pins, stepped locating)  
     locating techniques 179  
         application summary matrix 213  
         assemblability 184, 185,  
             187–189, 214  
         best practices 212  
         composite tolerance 196–199  
         considerations, manufacturing  
             189, 190  
         critical considerations 212  
         datum 184, 185, 186  
         design process 187  
         design requirements 181  
         differently sized holes 196  
         dual position control frames 199  
         equation summary 214  
         exact constraint design 181, 186  
         fixed and floating fasteners  
             183–185  
         functional datums 185  
         GD&T 183, 185  
         hardware 188, 191, 194, 195, 202,  
             203, 206–208  
         interchangeability 187, 214  
         kinematic fixturing 186  
         manufacturing considerations 190  
         minimum constraint design 186  
         MMC 183–185  
         press-fit 182, 184, 185, 188, 214  
         repeatability error 186, 196,  
             210, 211  
         resources 181  
         RFS 185  
         the two hole problem 182  
         three holes / three pins / two faces  
             210, 213, 214  
         two holes / one round pin and  
             one diamond pin / two holes 204,  
             213, 214  
         two holes / two pins / one hole and  
             one slot 199, 213, 214  
         two holes / two pins / one slot 209,  
             213, 214  
         two holes / two pins / two holes  
             192, 213, 214  
     lock nuts (see: nuts, prevailing torque  
         hex lock nuts)  
     lock washers (see: washers, high collar  
         lock washers)
- lockout/tagout 69, 81, 90  
 loss probability 686  
 low head cap screws (see: screws, low head)  
 lubrication  
     boundary 503, 505, 506  
     bushings 506, 509  
     full film 503, 504  
     gears 596, 598  
     hydrodynamic 504  
     hydrostatic 504  
     machine safety 69  
     mixed film 505  
     plain bearings 503, 506, 509  
     plain linear bearings 535, 537  
     rolling bearings 511, 530  
     thin film 503

## M

- machinability 373, 380, 383  
 machine design (see: design)  
 machine efficiency 695, 696  
     cost 696  
     quality rate 695, 696  
 machine manuals 50, 51, 53, 63, 71, 75,  
 82, 90  
 machine performance 695  
     best practices 699  
     critical considerations 698  
     metrics 696, 697  
     resources 683  
 machine reliability 683  
     best practices 699  
     calculation 684  
     critical considerations 698  
     FMECA (see: FMECA)  
     mean time between failures  
         (MTBF) 684  
     mean time to failure (MTTF) 684  
     resources 683  
 machine safeguarding 51  
     books 74  
     codes 72  
     critical considerations 65  
     designed-into-the-machine 52  
     guards, adjustable 55–57  
     guards, barrier 52–54, 56–58, 61  
     guards, dimensions of openings 55  
     guards, fixed 55–57, 80, 88  
     guards, interlocking 55–58, 60, 77,  
         80, 88

- guards, self-adjusting 55–57  
 instructions 51, 53, 62–64, 66–68, 70, 82, 90  
 manuals 51, 53, 62–64, 75, 82, 90  
 procedural 62, 52, 53  
 protective devices 52, 53, 58–62, 80, 81, 87, 88  
 protective devices, gates 56, 58, 61  
 protective devices, proximity detection 58, 60  
 protective devices, pull-back 53, 58, 59  
 protective devices, restraints 58, 59  
 protective devices, two-hand controls 53, 58, 60, 61, 77, 81  
 regulations 72  
 resources 71  
 standards 76, 37, 40, 46, 47, 49, 51, 55, 56, 58, 65, 68, 70–73  
 warnings 51–53, 62–65, 74, 90  
 web sites 84, 85
- machine safety (see also: machine safeguarding) 35, 47, 51, 65, 71  
 atmosphere 66, 68, 82  
 books 74  
 codes 72  
 critical considerations 51, 65, 71  
 design process 47  
 emergency stop 70, 71, 81, 90  
 emission of airborne substances 66, 90  
 explosive atmospheres 68, 82  
 goals 65  
 heat 66, 80, 86, 90  
 laser 66  
 light 66, 69  
 lockout/tagout 69, 81, 90  
 lubrication 69  
 moving the machine 68  
 noise 66, 67, 91  
 other issues 65  
 radiation 66  
 regulations 55, 69, 72  
 resources 71  
 signals 69, 81, 89, 90  
 stability 68  
 standards 40, 46, 47, 49, 51, 55, 56, 59, 65, 68–72, 76  
 vibration 66–68  
 warning signals 69, 81, 89, 90  
 web sites 84
- machine screw nuts (see: nuts)
- machining
- at assembly 133, 134  
 surface finish 395  
 tolerances 102, 190
- maintenance 39, 54, 62, 70, 133, 685  
 manuals 63, 75, 82, 90, 51, 53, 62  
 manufacturing equipment (see: machine)  
 manufacturing method tolerance 102, 190  
 mass density 374, 385, 387, 388  
 mass moments of inertia equations 22, 617, 618  
 materials 371  
 AISI 371, 372  
 alloy steel 372, 377, 380, 384, 385  
 aluminum 373, 377, 379, 387  
 bearings 506, 530  
 best practices 391  
 carbon content 371, 373, 378, 380, 406  
 carbon steel 373, 380, 402  
 ceramics 376, 378  
 code systems 371–373  
 cold rolled steel 380, 381  
 commonly used 218, 365, 366, 371, 376, 377  
 compressive strength 374, 388  
 corrosion resistance 375, 378, 379, 407–409  
 critical considerations 390  
 ductility 376, 380, 399  
 fastener 294  
 gears 595, 597, 603  
 hardness (see: hardness)  
 heat treatment (see: heat treatment)  
 hot rolled steel 380, 381  
 machinability 373, 380, 383  
 mass density 374, 385, 387, 388, 419  
 metals nomenclature 371–373  
 modulus of elasticity 375, 418, 461  
 modulus of rigidity 375, 386, 387, 419, 461  
 non-metals 376–378, 388  
 notch sensitivity 382  
 plastics 376–378, 388  
 properties 372, 383–388, 419, 420, 461  
 resources 371, 372  
 SAE 295, 371, 372  
 shafts 548, 549  
 shear ultimate strength 374, 383  
 shear yield strength 374
- stainless steel 378, 386, 387, 418, 419, 461  
 steel numbering 371, 372  
 steel, alloy 372, 377, 380, 384, 385  
 steel, carbon 373, 380, 402  
 steel, cold rolled 380, 381  
 steel, hot rolled 380, 381  
 steel, properties 373–376, 380, 384, 385, 419, 420, 461  
 steel, stainless 378, 386, 387, 418, 419  
 steel, surface quality 381, 418  
 steel, tool 372, 381–383, 385, 403  
 stock sizes 389, 421  
 tensile yield strength 295, 374, 382, 399  
 thermal conductivity 376  
 thermal expansion 375, 376, 379  
 titanium 379, 386, 387  
 tool steel 372, 381–383, 385, 403  
 ultimate shear strength 374, 383  
 ultimate tensile strength 374, 383, 420  
 wear resistance 382, 373, 378, 379, 381, 400, 409, 410  
 weldments 365, 366  
 yield strength, tensile 295, 374, 382, 399
- matrix, decision or Pugh 9  
 max material condition (see: MMC)  
 maximum material boundary (see: MMB)  
 mean 137, 138, 141–143, 159  
 mean time between failures (see: MTBF)  
 mean time to failure (see: MTTF)  
 metals (see: materials)  
 meter-in circuit 468  
 meter-out circuit 468  
 metric  
 prefixes 16, 17  
 units 16, 17
- minimum constraint design 186  
 miter gear (see also: bevel gear) 582, 607  
 MMB 161, 163, 169, 170  
 MMC 126, 152, 153, 156, 163, 169, 170, 183–185  
 modified Goodman diagram 423, 556  
 modifier  
 effect on tolerance 126, 152–155, 161, 163, 169, 170  
 LMC 126, 152, 154, 163, 164  
 MMC 126, 152, 153, 156, 163  
 RFS 126, 185

# 710 Index

module, gear 576, 601  
 modulus of elasticity 375, 418, 419  
 modulus of rigidity 375, 419  
 moment of inertia, gearboxes (see: gearboxes)  
 moments of inertia, area, equations 21  
 moments of inertia, mass, equations 22, 617, 618  
 Mont Carlo simulation 145, 160, 175  
 motors 482  
 AC (see: AC motors)  
 best practices 499  
 C-face 493  
 constant speed 484  
 continuous motion 484, 486, 487, 495  
 controls 490, 491, 493  
 critical considerations 499  
 DC (see: DC motors)  
 D-flange 493  
 duty cycle 484, 494  
 electrical power 482  
 enclosures 484, 491, 493, 494  
 frames 484, 493, 494  
 full-load speed (RPM) 484, 489  
 gearboxes (see: gearboxes)  
 horsepower 484, 486, 488  
 IEC 482–484, 486, 488, 493, 494  
 inertia 489, 494, 495, 497  
 INSUL CLASS (insulation class) 484  
 intermittent motion 484, 486, 494  
 kW 483, 497  
 manufacturer's type 483  
 maximum ambient temperature 483  
 mounting 488, 493, 494  
 NEMA 482–484, 486, 487, 493, 494  
 ODP 494  
 overheating 483, 495  
 overload protection 491  
 rated horsepower 483, 488  
 resources 482  
 RMS torque 495, 497  
 selection 487, 491  
 sizing 494, 497  
 speed control 489, 491  
 starting 490  
 stopping 491  
 terminology 483, 484, 490  
 torque 483, 486, 488, 489, 494, 495, 497

moving equipment 68  
 MTBF 684  
 MTTF 684

**N**

natural frequency  
 shafts 556–559  
 springs 423, 432, 444

needle roller bearings 517  
 needle roller thrust bearings 518

NEMA 482, 483, 484, 486, 487

Neuber's constant for notch sensitivity 28, 30, 557

NIOSH 46, 67, 85

nitride 382, 409–411, 587

noise 66, 67, 91  
 of gearboxes (see: gearboxes)

non-metals 376, 378, 389

non-normal distribution 145

normal distribution 137–139

normal, standard (see: standard normal)

normalizing 401

notch sensitivity 28, 30, 382, 557

nuts (see also: fasteners) 304, 287, 294  
 hex machine screw nuts 343  
 hex nuts, data, inch 342, 343  
 hex nuts, data, metric 344  
 hex thin nuts (jam nuts) 304  
 hex thin nuts, data, inch 342  
 hex thin nuts, data, metric 344  
 linear motion screws (see: linear motion screws)  
 prevailing torque hex lock nuts 305  
 prevailing torque hex lock nuts, data, inch 344  
 prevailing torque hex lock nuts, data, metric 345  
 stripping 295

**O**

OB 162, 163  
 OEE 697, 698

Oldham coupling 569, 573

open center circuit 467

operator capabilities and limitations 37, 41–43, 86

orientation  
 factor 157, 158, 160  
 tolerances 173, 122, 147, 151, 160  
 variation 155, 158, 159, 171

outer boundary (see: OB)

overall equipment effectiveness (see: OEE)

overheating motors 483, 495

**P**

parallel keys (see: keys)

parallelism 122, 123, 173

passivation 408, 410, 411

PEEK 376–388

performance (see: machine performance)

perimeters and areas equations 20

perpendicularity 122, 123, 147, 173

physical capabilities and limitations 37, 41–43, 86

pinion 578, 580, 581, 587, 592, 594, 595

pins 219  
 bearing stress 217, 218  
 clevis (see: clevis pins)  
 coiled spring (see: spring pins)  
 cotter (see: cotter pins)  
 datum: practical considerations 186  
 diamond (see: stepped locating pins)  
 dowel (see: dowel)  
 fixed and floating fasteners 183  
 grooved (see: grooved pins)  
 locating (see: stepped locating pins)  
 materials 218  
 precision locating 182, 191  
 precision locating dimensions 188, 194, 195, 202, 203, 206–208  
 pullout dowel (see: dowel, withdrawal)  
 resources 217  
 shear 217, 218  
 slotted spring (see: spring pins)  
 spring (see: coiled spring pins)  
 stepped locating (see: stepped locating pins)  
 stress 217, 218  
 types, selector 219–222  
 withdrawal dowel (see: dowel, withdrawal)

pipe and port threads 281–285

pitch  
   circular 576, 577, 579  
   diametral 576, 577, 579, 592  
   gear (coarse and fine) 579, 580  
   linear motion screws 664  
 pitch diameter  
   belts and chains 628, 630, 631  
   gears 576, 577, 589  
 pitch circle, gears 577, 578, 581, 587, 591, 592  
 pitch point 577  
 plain bearings 503  
   bearing pressure 504, 507  
   best practices 510  
   bushings 503, 534  
   critical considerations 510  
   friction 503–507  
   heat & temperature 506, 507  
   length 507  
   linear (see: linear bearings, plain)  
   loads 507, 508  
   lubrication 503–506  
   materials 506, 508  
   oil-free 505  
   plastic 506  
   PV 507, 508  
   resources 503  
   selection and sizing 509  
   shafts 505–508  
   sleeve 506  
   thrust 506  
 planetary gear trains 582, 589  
 plastics 376, 377, 388  
 plug weld 360  
 pneumatics 466  
   actuator symbols 471  
   actuator, air cylinder 468  
   actuator, compression ratio 475  
   actuator, Cv 474, 475  
   actuator, double acting 468  
   actuator, flow rate 474, 475  
   actuator, force 472  
   actuator, kinetic energy 472, 473, 475  
   actuator, misalignment 473  
   actuator, rod buckling 473  
   actuator, rotary 468, 470, 472–475  
   actuator, single acting 468, 478  
   actuator, sizing procedure 472  
   actuator, speed 468, 472, 478  
   actuator, wear 473

best practices 481  
 circuits 467  
 closed center circuit 467  
 critical considerations 480, 481  
 Cv 472, 480  
 Cv calculation 474, 475  
 kinetic energy, actuator 472, 473, 475  
 meter-in circuit 468  
 meter-out circuit 468  
 open center circuit 467  
 pressure 467  
 regulation 467  
 reservoir 467  
 resources 466  
 speed, actuator 468, 472, 478  
 symbols 468, 469, 471, 479  
 valves 476, 478, 479  
 valves, ports 477, 478  
 valves, positions 477, 478  
 valves, sizing 480  
 valves, symbols 479  
 valves, vacuum 477  
 valves, ways 477, 478  
 poka-yoke 11  
 port threads (see: pipe and port threads)  
 position tolerance 125, 151, 155, 160, 161, 169, 185  
 power  
   AC 482, 484  
   belts and chain 632, 637, 640, 644, 649, 658, 660  
   DC 482  
   equations 33  
   linear motion screws 667, 668  
   shafts 550, 553  
   v-belt (see: v-belt)  
 power screws (see: lead screw)  
 power transmission devices 543  
 precision locating (see: locating techniques)  
 pre-hardening 407  
 preliminary hazard analysis 50  
 preload, bolt 295, 297, 298  
 press-fit criterion 214  
 pressure  
   air 467  
   angle 576, 577, 579–581, 610  
 prevailing torque hex lock nuts (see: nuts, prevailing torque)

preventative maintenance (see: maintenance)  
 procedural safeguarding (see: machine safeguarding)  
 process capability index 141, 142, 188  
 process efficiency (see: machine efficiency)  
 profile 124, 125, 168, 171–174  
 proof 295–297  
 protective devices (see: machine safeguarding)  
 PTFE 281, 376, 388, 409  
 Pugh matrix 9  
 pulley 627  
 pullout dowel (see: dowel, withdrawal)  
 PV  
   lead screw 674  
   plain bearings 507, 508  
   plain linear bearings 536, 537

## Q

quality rate 695, 696  
 quality ratings, gears 589–591  
 quenching 401

## R

rack and pinion (see also: gears) 579, 585, 587  
   forces on shafts 618  
   interference 581  
   tooth form 578–580  
 radiation 66  
 Raleigh's method 558, 559  
 rate, repair 684  
 rated horsepower, motors 483, 488  
 ratio  
   gear 576, 577, 582, 587, 588  
   gearboxes (see: gearboxes)  
 Rc (see: Rockwell hardness)  
 reaching 38, 41, 42, 46  
 reducer (see: gearboxes)  
 regardless of feature size (see: RFS)  
 regulator 467, 479  
 reliability (see: machine reliability)  
 repair rate 684  
 repeatability error 186, 196, 210  
 research design 8  
 retaining rings 225

## 712 Index

- best practices 226  
 clearance 268, 270, 272, 274–277  
 critical considerations 226  
 designations 225, 226  
 e-ring, data, inch 276  
 e-ring, data, metric 277  
 external, data, inch 272, 273  
 external, data, metric 274, 275  
 grooves 225, 268, 269–277  
 internal, data, inch 268, 269  
 internal, data, metric 270, 271  
 resources 217  
 standards 225, 226  
 thrust 225  
 types 225, 226
- RFS 126, 185  
 right triangle equations 19  
 rigid coupling 564, 565, 573  
 risk  
     and reliability 685, 689, 691  
     and safety 47, 51, 62, 69, 74, 76, 82, 86, 91  
     safety, analysis 48, 49, 51, 73  
     safety, assessment 47–49, 51, 78, 79, 83, 85, 86, 89  
     safety, evaluation 49  
     safety, reduction 47–51, 53, 62, 73, 78, 83, 85, 86  
 risk priority number (see: RPN)  
 RMC torque 620, 625  
 RMS torque 495, 496, 497  
 Rockwell hardness 399, 400  
 roll pins (see: spring pins)  
 roller chain (see: chain)  
 roller screw 672  
 rolling bearings 510  
     ABEC 520–523  
     angular contact ball bearings 515, 519, 520  
     angular misalignment 514–518, 520, 531  
     applications 519  
     applied load 527, 528  
     arrangement design 525–527  
     axial constraint 525–527  
     axial displacement 512, 525  
     axial load 514–520, 525, 527  
     basic dynamic load rating 513, 527 - 529  
     bearing arrangements 525–527  
     best practices 534  
     bore 512, 520  
     cage 512, 518  
     cavitation 525–527  
     characteristics 512  
     clearance, internal 513, 521, 525  
     combined load 515, 517, 519, 520, 525, 527, 528  
     critical considerations 533  
     cylindrical roller bearings 516  
     deep groove ball bearings 514  
     dimensions and tolerances 520–524  
     drag 530  
     dynamic load 513, 527–529  
     equivalent load 527, 528, 530  
     failure 518, 529, 530  
     fits 521–523  
     fluctuating load 528  
     forces 527, 528  
     four-point contact ball bearings 515, 516  
     friction 530  
     grease, speeds 511  
     heat and temperature 513  
     housing dimensions and tolerances 520–524  
     internal clearance 513, 521, 525  
     life 529, 530  
     limiting speed 513  
     load rating 513, 527, 529  
     loads 527, 528  
     lubrication 511, 513, 530  
     maintenance free 511  
     minimum load 528  
     needle roller bearings 517  
     non-preloaded 525  
     operating speed 513  
     precision 520, 521  
     preloaded 525  
     race 512, 521  
     resources 511  
     safety factor 530, 531  
     seals 511, 520  
     selection and sizing 519, 520, 531  
     self-aligning ball bearings 514, 515  
     separable 512, 513, 517, 518, 520  
     service factor 530  
     shaft dimensions and tolerances 520–524  
     shaft finish 521  
     shaft misalignment 514–517, 519, 520, 554  
     shields 511  
     shock 530  
     speed 511, 513, 514, 518, 519, 525  
     spherical roller bearings 516, 517  
     starting torque 514  
     static load 513, 527–529  
     tapered bore 512, 526  
     tapered roller bearings 516, 517  
     temperature 511, 513  
     thrust bearings 518–520, 528  
     tolerances 520–524  
     types 514, 519, 520
- root  
     gear tooth 580  
     weld 360  
 root diameter  
     gear 600, 601  
     linear motion screws 666, 669, 671  
 root mean cubed (see: RMC)  
 root mean square (see: RMS)  
 root sum of squares method 138, 142, 146  
 rotary actuator (see: pneumatics, actuator)  
 rotary motion equations 32  
 rotating shafts (see: shafts)  
 roughness (see: surface finish)  
 RPN 689–691  
 rule 8  
 runout  
     circular 123, 124, 174  
     gears 589, 591  
     total 124, 174
- S**
- SAE 295, 371, 372  
 safeguarding (see: machine safeguarding)  
 safety (see also: machine safety)  
     resources 71  
     and ergonomics 38  
 safety category 693–695  
 safety factors 13, 14  
 scale, measuring 8  
 scrap 696, 697  
 screw selector slide chart 13  
 screws (see also: fasteners)  
     ball (see: ball screw)  
     clearance 302–304, 310, 312, 314, 316, 330, 332, 334, 336, 338, 340  
     hex head cap screws 304  
     hex head cap screw, data, inch 338, 339  
     hex head cap screw, data, metric 340, 341

- hex socket button head cap screws 304  
 hex socket button head cap screw, data, inch 330, 331  
 hex socket button head cap screw, data, metric 332, 333  
 hex socket flat countersunk head cap screws 304  
 hex socket flat countersunk head cap screw, data, inch 334, 335  
 hex socket flat countersunk head cap screw, data, metric 336, 337  
 hex socket head cap screws 301  
 hex socket head cap screws, data, inch 310, 311  
 hex socket head cap screws, data, metric 312, 313  
 hex socket head shoulder screws 303  
 hex socket head shoulder screw, data, inch 326, 327  
 hex socket head shoulder screw, data, metric 328, 329  
 hex socket set screws 302, 303  
 hex socket set, cone point, data, inch 318  
 hex socket set, cone point, data, metric 322  
 hex socket set, cup point, data, inch 319  
 hex socket set, cup point, data, metric 323  
 hex socket set, dog point, data metric 324  
 hex socket set, flat point, data, inch 321  
 hex socket set, flat point, data, metric 325  
 hex socket set, half dog point, data, inch 320  
 hex socket set, half dog point, data, metric 324  
 hex socket set, locking 303  
 lead (see: lead screw)  
 low head hex socket cap screw 302  
 low head hex socket cap screws, data, inch 314, 315  
 low head hex socket cap screws, data, metric 316, 317  
 roller (see: roller screw)  
 stripping 295  
 seals, rolling bearings 511, 514, 520
- self-aligning ball bearings 514, 515  
 set screws (see: screws, hex socket set)  
 shaft speed, critical 26, 556, 559  
 shafts 547  
     attachment 548, 563, 589  
     axial loads 553  
     axial location 525–527  
     bearing, plain 504–509  
     bearing, plain linear 535, 538, 540  
     bearing, rotating 512, 513, 518, 522, 523, 525–527  
     best practices 562  
     couplings (see: couplings)  
     critical considerations 562  
     critical speeds 26, 556–559  
     deflection 553, 554, 560  
     design 558  
     diameter 561  
     fatigue 555, 556, 561  
     forces on 549, 550, 553, 617, 618  
     hardness 548, 549  
     hollow 548  
     keys 219, 223, 224, 547, 548, 563, 589  
     materials 548, 549  
     misalignment 564  
     motors, NEMA 637  
     natural frequency 556, 557  
     notch sensitivity 557  
     power 553  
     resources 547  
     rigidity 548, 558  
     set screws 303, 548  
     speed 26, 556–559  
     splines 540  
     stepped 553, 554  
     stress 548, 555, 556, 561  
     stress concentration 548, 555  
     tolerancing for bearings 521–523  
     vibration 557–559  
     whirl 557–559
- shear  
     keys 217, 218, 223  
     pins 217–219, 221, 222, 238, 240, 242, 244, 245, 248, 250  
     shafts 554, 555  
     stress 27, 217, 218  
     ultimate strength 374, 383  
     yield strength 374, 382, 383
- sheave 627, 630, 641  
 shock resisting tool steel 382, 383, 385  
 shoulder screws (see: screws, hex socket head shoulder)
- signals, warning 69, 81, 89, 90  
 single acting 468, 478  
 six-sigma 142, 146  
 sleeve bearings (see: plain bearings or plain linear bearings)  
 slender column equations 25, 670  
 slide chart, screw selector 13  
 slides (see: linear bearings)  
 slit coupling 567, 573  
 slotted spring pins (see: spring pins)  
 snap rings (see: retaining rings, e-rings)  
 socket flat head cap screws (see: screws, hex socket flat)  
 socket head cap screws (see: screws, hex socket head cap)  
 socket head shoulder screws (see: screws, hex socket head shoulder)  
 SolidWorks®  
     fasteners and washers 309  
     pins, keys, and retaining rings 278  
 SPC 137, 142  
 specification  
     design 3  
     limits 137, 141  
 speed (see also: velocity)  
     bearing, plain 503, 506, 507  
     bearing, rolling 511, 513, 519, 537  
     belts 627–630, 632, 634, 645, 647, 649  
     chain 627, 628, 655, 658, 660  
     couplings 564, 565, 567, 568, 571  
     gearboxes 614, 615, 620, 621, 623, 625  
     gears 589, 591, 596, 598, 599, 607  
     linear motion screws 670–672, 674  
     shafts 26, 556–559  
     speed ratio, belts and chains 627, 645, 647, 649  
     spherical roller bearings 516, 517  
     spherical roller thrust bearings 518  
     spiral bevel gear 585, 608  
     split pin (see: cotter pin)  
     spring anchor pins (see: grooved pins)  
     spring pins  
         coiled 221  
         coiled, data, inch 238, 239  
         coiled, data, metric 242, 243  
         slotted 221  
         slotted, data, inch 240, 241  
         slotted, data, metric 244, 245, 247
- springs 415  
     active coils 422  
     Belleville (see Belleville springs)

## 714 Index

- best practices 465, 466  
 clearance 430  
 clock, power, or motor 418  
 compression (see: compression springs)  
 constant force 417  
 critical considerations 465  
 drawbar assembly 416  
 endurance limit 425  
 extension (see: extension springs)  
 fatigue 423, 424, 425  
 garter 418  
 gas 418  
 hair or spiral 417  
 helical coil compression (see: helical coil compression)  
 helical coil extension (see: helical coil extension)  
 helical coil terminology 422  
 helical coil torsion (see: torsion)  
 high temperature 418, 419, 422  
 leaf or beam 417  
 materials 418–420  
 mean coil diameter 422  
 natural frequency 423, 432, 444  
 pitch, helical coil 426, 432  
 resources 415  
 shock loading 419, 441, 457  
 spring constant 422, 432, 444, 452  
 spring index 422, 432, 443, 451  
 spring rate (see: spring constant)  
 spring washers 416, 423, 456  
 stress 423–427, 429, 432, 433, 441, 442, 444, 446, 451, 452, 459–461  
 stress relaxation 418, 422  
 surface quality 418  
 surge 423, 441  
 torsion (see: torsion springs)  
 torsion bar 417  
 types 415  
 volute 417  
 wire diameters 421
- sprocket  
 chain 627, 655, 661  
 timing belt 627, 630
- spur gear (see also: gears) 582, 583, 599  
 addendum 576, 577, 581, 601  
 backlash 591–594  
 center distance 576–578, 591–594, 600, 601  
 circular pitch 576, 577, 579, 600, 601  
 clearance 576, 591
- conjugate action 577, 578  
 contact ratio 580, 601  
 dedendum 576, 577, 601  
 diametral pitch 576, 579, 580, 592, 600, 602  
 equations 600–602  
 horsepower 602  
 interference 580, 581, 592  
 involute 578, 579  
 Lewis formula with Barth revision 600, 602  
 lubrication 592, 596, 598, 599  
 module 576, 601  
 number of teeth 576, 581, 588, 594, 600–602  
 pinion 580, 592, 594, 595  
 pitch 579, 580, 589  
 pitch circle 578, 581, 591, 592  
 pitch diameter 576, 600–602  
 pitch line 591, 596, 599, 602  
 pitch point 577  
 pressure angle 576, 577  
 root 580, 600, 601  
 selection and sizing 599  
 shafts 589, 592  
 stress 595, 600, 603  
 terminology 576, 577  
 tooth form 577–580, 601  
 tooth strength 592, 599, 600  
 undercutting 580–582, 601  
 velocity ratio 577, 578, 582, 587, 588
- stack-ups (see: tolerance stack-ups)  
 stainless steel 378, 386, 387, 408, 418, 419, 461
- standard deviation 137, 138, 141–144, 159  
 standard normal 138–141  
 statistical  
     tolerance stack-up 137  
     process control 138
- steel (see: materials)
- stepped locating pins 191, 220  
 data, metric 237  
 precision locating dimensions 202, 206–208
- straight bevel gear (see: bevel gear)  
 straightness 120, 121  
 strain and stress 27, 375  
 strain hardening 401
- strength (see also: materials)  
 endurance 29, 297, 424, 425  
 shear 221, 222, 303, 374, 379, 383
- tensile 295, 374, 375, 379, 383, 399, 418, 422
- stress  
 axial 27  
 bearing 27, 218, 223  
 bending 27  
 bolts 295–297  
 coil (see: springs)  
 hook (see: springs)  
 keys 217–219  
 pins 217, 218  
 shear 27, 218, 223, 295, 374, 375, 423, 432  
 tensile 27, 295–297  
 three dimensional 27  
 torsion 27, 423, 446  
 Von Mises 27
- stress and strain equations 27  
 stress relieving 401, 403  
 weldments 366
- stripping 295
- surface areas and volumes equations 21  
 surface finish 391  
 best practices 398  
 common values 395–397  
 comparator 13  
 critical considerations 398  
 lay symbols 393  
 machining 397  
 resources 391  
 symbols 392–394  
 tolerances 394
- surface roughness (see: surface finish)  
 surface texture (see: surface finish)  
 surface treatment 407  
 anodizing 409–411, 379  
 best practices 412  
 black oxide 408, 410, 411, 294, 366  
 buildup 408–410  
 chrome plating 408, 410, 411  
 corrosion resistance 375, 379, 380  
 critical considerations 412  
 electroless nickel plating 409–411  
 electroplating 408, 410, 411  
 electropolishing 408, 410, 411  
 friction reducing 383, 410  
 hardness 399, 408, 409  
 nitride 382, 409–411  
 passivation 408, 410, 411  
 properties 408–411  
 resources 407  
 roughness 408  
 selection 410, 411

- titanium nitride 409–411, 382  
 types 408–411  
 wear resistance 383, 408–410  
 weldments 366  
 zinc electroplating 408, 410,  
 411, 295
- synchronous  
 belt (see: timing belt)  
 motor 484, 487  
 speed 484, 486, 497
- synthesis, design 9
- T**
- tap drills 288  
 depths 288, 293  
 sizes 289–292
- tapered keys 224
- tapered roller bearings 516, 517
- tee joint 360
- tempering 401
- tensile load on bolts 295–297
- tensile yield strength 374
- tension  
 chain 655, 658  
 flat belt drive 629, 632–634  
 timing belt drive 630, 649, 650  
 v-belt drive 638
- thermal conductivity 376
- thermal expansion 18, 375, 379,  
 384–387
- thermoplastic 376
- thermoset 376
- thickness  
 gauge 13  
 sheet metal 389  
 steel stock 389
- thin nuts (see: nuts)
- threaded fasteners (see: fasteners)
- threaded inserts 306  
 best practices 308  
 data, inch 352, 353  
 data, metric 354, 355  
 installation 307
- threads, fastener (see: fastener threads)
- threads, pipe and port (see: pipe and port threads)
- three holes / three pins / two faces 210
- three-phase power 482
- throat of weld 360
- through hardening 400, 402, 403
- thrust bearings 506, 518–520, 527, 528, 553, 673
- tightening torque 298–301
- timing belt (see also: belts) 629, 630  
 calculations 649  
 forces on shafts 550, 617, 650  
 pitch 631  
 pitch diameter 649  
 power 649  
 selection and sizing 648  
 service factor 650  
 speed 628, 629, 649  
 sprocket 627, 630  
 tension 630, 649, 650  
 tooth shear 630  
 width 651
- titanium 379, 386, 387
- titanium nitride 382, 409–411
- toe of weld 360
- tolerance (see also: fits)  
 (see also: limits)  
 analysis (see: tolerance stack-ups)  
 and dimensions 93  
 assignment 133–135  
 best practices 116, 127, 177  
 critical considerations 116, 126, 176  
 grades 95–97, 100, 102  
 hardware tables 188, 194, 195, 202, 203, 206–208  
 implied 117  
 machining 102, 190  
 on drawings 116  
 resources 95, 116, 128  
 surface finish 394
- tolerance stack-ups 127  
 angularity 173  
 application summary 175  
 applications 146  
 best practices 177  
 boundary example problem: spring pin 164  
 boundaries 161–163  
 calculation 128, 129, 134  
 chain 129, 132  
 combined (worst case / statistical) 143, 144  
 critical considerations 176  
 datum shift 168–171  
 design practice 128  
 floating and fixed fasteners 161  
 form tolerance on datum surface 148
- hardware tables 188, 194, 195, 202, 203, 206–208  
 LMC 152, 163, 164  
 mean 137–139, 141–143, 159  
 MMC 152, 153, 156, 163  
 Monte Carlo 145, 146, 160, 175  
 multiple assembly conditions 146  
 normal distribution 137–139  
 orientation tolerances 173  
 parallelism 173  
 perpendicularity 173  
 plus/minus tolerancing and GD&T 147  
 position tolerance 151  
 procedure 129  
 profile tolerances 171  
 resources 128  
 root sum of squares 138, 142, 146  
 runout tolerances 174  
 standard deviation 137, 138, 141–144, 159  
 statistical 137, 138, 141–146, 159, 175  
 two dimensional: location and orientation variation 155  
 worst-case 135, 136, 143–145, 163, 175
- tolerancing (see: tolerance)
- tool steel 372, 381–383, 385, 403
- torque  
 couplings (see: couplings)  
 gearboxes (see: gearboxes)  
 linear motion screws (see: linear motion screws)  
 tightening, bolts 298–301
- torsion springs 416, 417, 450  
 (see also: springs)  
 active coils 422, 451  
 bending stress 452  
 body length 451  
 catalog selection steps 451  
 deflection 423, 451, 452  
 design steps 454  
 direction 450  
 end types 450  
 fatigue 423, 425  
 mandrel 451  
 natural frequency 423  
 parallel 452  
 sizing equations 451  
 spring constant 422, 452  
 spring index 422, 451  
 stress 452

**716** Index

torque 451, 452  
 wire diameter 421, 422, 451  
 total machine efficiency 696  
 total runout 124, 174  
 transition fit (see: fits)  
 triangle equations 19  
 two holes / one round pin and one diamond pin / two holes 204  
 two holes / two pins / one hole and one slot 199  
 two holes / two pins / one slot 209  
 two holes / two pins / two holes 192  
   composite tolerance 196, 198  
   dual position control frames 199  
   variation: differently sized holes 196  
 two-hole locating (see: locating techniques)

**U**

u-joint 565, 566  
 ultimate shear strength 374, 383  
 ultimate tensile strength 374, 383, 420  
 undercutting 580–582  
 undervoltage 483  
 units  
   commonly used 16  
   conversions 17  
   engineering 15  
   foot-pound-second system (FPS) 16  
   Imperial systems 16  
   inch-pound-second system (IPS) 16  
   metric prefixes 17  
   resources 15  
 uptime 684

**V**

valves (see: pneumatics, valves)  
 variation (see also: tolerance)  
   assembly 133  
 v-belt (see also: belts) 627, 630  
   bending frequency 638  
   calculations 628, 629, 637, 638  
   classical 630, 631, 640  
   cross section 630, 631  
   Eytelwein's equation 636, 638  
   forces on shafts 550, 638  
   narrow 630, 640  
   pitch diameter 628, 630  
   power 637, 644

selection and sizing 636  
 service factor 639  
 sheave 627, 630, 638, 641  
 slip 629, 638  
 speed 628, 630  
 tension 638  
 torque 638  
 velocity (see also: speed)  
   linear motion 31  
   ratio, gears 576, 578, 582, 587, 588, 592, 600  
   rotary motion 32  
 vibration 66, 67, 221, 286, 305, 306, 493  
   Raleigh's method 558, 559  
   shafts 556–559  
 Vickers 399, 400  
 volumes and surface areas equations 21

**W**

warnings 51–53, 62–64, 74, 75, 90  
 warping (see: distortion)  
 washers  
   best practices 299  
   critical considerations 298  
   fender (see: washers, wide)  
   flat (see: washers, plain)  
   heavy duty 305  
   high collar lock washers 306  
   high collar lock washers, data, inch 350  
   high collar lock washers, data, metric 351  
   lock washers (see: washers, high collar)  
   plain regular flat washers 305  
   plain regular flat washers, data, inch 346  
   plain regular flat washers, data, metric 348  
   resources 285  
   spring (see: springs, spring washers)  
   standard (see: plain regular flat)  
   wide 305  
   wide washers, data, inch 347  
   wide washers, data, metric 349  
 waviness (see: surface finish)  
 weld (see: welds)  
 welded joints 360, 365, 366  
 weldments (see also: welds) 359  
   best practices 368  
   critical considerations 367

drawings 364, 365  
 fatigue 359, 366  
 materials 365, 366  
 resources 359  
 strength 359, 365  
 stress relieve 366  
 surface treatment 366  
 welds (see also: weldments) 359  
   best practices 368  
   critical considerations 367  
   resources 359  
   symbols 361–364  
   terminology 360  
   types 360  
 what if analysis 49  
 whirl 557, 558, 670, 671  
 wide washers (see: washers, wide)  
 wire diameters, spring materials 421  
 withdrawal dowel (see: dowel, withdrawal)  
 Woodruff keys 224  
   data, inch 264, 265  
   data, metric 266  
 work equations 33  
 workspace  
   access openings 39, 43–45, 80, 87  
   clearance 39, 43, 87  
   dimensions 39, 43–45, 80, 87  
   enclosures 39  
 worm gear (see also: gears) 586, 608  
   efficiency 609  
   equations 611  
   forces on shafts 552, 610  
   materials 595  
 worst-case tolerance stack-up 135, 136, 143–145, 163, 175  
 wrench clearance 301, 304, 338, 340, 342–345

**Y**

yield strength 295, 374, 382, 399

**Z**

Zerol bevel gear (see also: bevel gear) 586  
 zinc electroplating 408, 410, 411, 294  
 Zirconia 378



