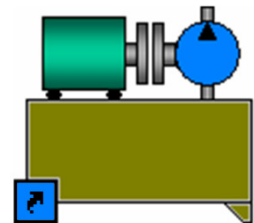


Hydraulic Systems Volume 1

Introduction to Hydraulics for Industry Professionals

*Dr. Medhat Kamel Bahr Khalil, Ph.D, CFPHS, CFPAL.
Director of Professional Education and Research Development,
Applied Technology Center, Milwaukee School of Engineering,
Milwaukee, WI, USA.*



CompuDraulic LLC
www.CompuDraulic.com

Hydraulic System Volume 1

Introduction to Hydraulics for Industry Professionals

ISBN: 978-0-692-62236-0

Printed in the United States of America

First Published by 2016

Revised by January 2019

All rights reserved for CompuDraulic LLC.
3850 Scenic Way, Franksville, WI, 53126 USA.
www.compudraulic.com

No part of this book may be reproduced or utilized in any form or by any means, electronic or physical, including photocopying and microfilming, without written permission from CompuDraulic LLC at the address above.

Disclaimer

It is always advisable to review the relevant standards and the recommendations from the system manufacturer. However, the content of this book provides guidelines based on the author's experience.

Any portion of information presented in this book could be not applicable for some applications due to various reasons. Since errors can occur in circuits, tables, and text, the author/publisher assumes no liability for the safe and/or satisfactory operation of any system designed based on the information in this book.

The author/publisher does not endorse or recommend any brand name product by including such brand name products in this book. Conversely the author/publisher does not disapprove any brand name product by not including such brand name in this book. The publisher obtained data from catalogs, literatures, and material from hydraulic components and systems manufacturers based on their permissions. The author/publisher welcomes additional data from other sources for future editions. This disclaimer is applicable for the workbook (if found). associated with this textbook

Hydraulic Systems Volume 1 Introduction to Hydraulics for Industry Professionals

PREFACE, 13

ACKNOWLEDGEMENT, 14

ABOUT THE BOOK, 15

ABOUT THE AUTHOR, 18

Chapter 1: Hydraulic Systems Overview, 19

1.1- Power Transmission and Control Systems, 20

1.2- Power Transmission and Control Systems Selection Criteria, 24

1.3- Power Transmission Systems General Features Comparison, 25

1.3.1- Application Characteristics, 25

1.3.2- Initial and Running Cost, 26

1.3.3- Precision of Motion, 26

1.3.4- Power to Weight Ratio, 27

1.3.5- Providing Linear Motion, 28

1.3.6- Efficiency of Energy Transmission, 28

1.3.7- Conclusion Table, 29

1.4- Fluid Power versus Fluid Mechanics, 30

1.5- Fluid Power Systems Classification, 30

1.5.1- Hydraulic versus Pneumatic, 31

1.5.2- Hydrostatic versus Hydrodynamic, 33

1.5.3- Open Circuit versus Closed Circuit, 34

1.5.4- Industrial versus Mobile Application, 35

1.6 -Basic Construction of Hydraulic Systems, 37

1.7- Advantages and Limitations of Hydraulic Systems, 40

1.7.1- Use of Hydraulic Fluids, 40

1.7.2- Power Transmission, 41

1.7.3- Controllability and System Design, 42

1.8- Industry Standards for Hydraulic Systems, 43

Chapter 2: Basic Concepts Review, 45

2.1- Basic Mechanics, 46

- 2.1.1- Effort and Flow Variables for Physical Systems, 46
- 2.1.2- Force, 48
- 2.1.3- Torque, 49
- 2.1.4- Energy, 50
- 2.1.5- Work, 51
- 2.1.6- Power, 53
 - 2.1.6.1- Power of a Linear Actuator (Hydraulic Cylinder), 53
 - 2.1.6.2- Power of a Rotational Actuator (Hydraulic Motor), 54
 - 2.1.6.3- Hydraulic Power Calculations, 56

2.2 – Basic Physics, 57

- 2.2.1- Pressure, 57
- 2.2.2- Atmospheric Pressure, 58
- 2.2.3- Absolute versus Gauge Pressure, 58
- 2.2.4- Pascal’s Law, 61
- 2.2.5- Pressure Head, 62

2.3- Basic Fluid Mechanics, 64

- 2.3.1- Flow Patterns, 63
 - 2.3.1.1- Laminar Flow, 64
 - 2.3.1.2- Turbulent Flow, 64
 - 2.3.1.3- Laminar versus Turbulent Flow, 65
- 2.3.2- Reynolds Number, 65
- 2.3.3- Typical Flow Speeds in a Hydraulic Conductor, 68
- 2.3.3- Conservation of Mass in Fluid Flow, 69
 - 2.3.4.1- Compressible Flow, 69
 - 2.3.4.2- Incompressible Flow, 72
- 2.3.5- Conservation of Energy in Fluid Flow, 74
 - 2.3.5.1- Bernoulli Equation for Ideal Fluid Flow, 74
 - 2.3.5.2- Bernoulli Equation for Real Fluid Flow, 77

2.3.6- Pressure Drop in Transmission Lines, 77

2.3.6.1- Frictional Pressure Losses in Hydraulic Lines, 78

2.3.6.2- Local Pressure Losses in Fittings, 83

2.3.6.3- Local Pressure Losses in Orifices, 85

2.3.6.4- Local Pressure Losses in Valves, 87

2.4- Basic Hydraulics, 89

2.4.1- Pressure-Load Relationship, 89

2.4.2- Flow-Speed Relationship, 90

2.4.3- Force Intensifiers, 92

2.4.4- Pressure Intensifiers, 93

2.4.5- Series versus Parallel Resistance, 95

Chapter 3: Hydraulic System Sizing Calculations, 96

3.1- Forward Path Power Losses in Hydraulic Systems, 97

3.2- Backward Path Power Accumulation in Hydraulic Systems, 98

3.2.1- Ideal Considerations in Hydraulic System Sizing, 99

3.2.2- Practical Considerations in Hydraulic System Sizing, 99

3.2.3- Case Study of Hydraulic System Sizing, 99

- Step 1: Quantify the Output Power of the Hydraulic Actuator, 100
- Step 2: Hydraulic Actuator Sizing and Pressure Requirements Identification, 101
- Step 3: Flow Requirements Identification, 102
- Step 4: Hydraulic Pump Sizing, 102
- Step 5: Calculate the Cylinder Input Power and Cylinder Efficiency, 102
- Step 6: Flow Distribution Analysis, 103
- Step 7: Hydraulic Conductors Sizing and Line Losses Calculations, 103
- Step 8: Valve Sizing and Valve Losses Calculations, 104
- Step 9: Quantify the Output Power of the Pump, 105
- Step 10: Prime-Mover Sizing, 105

Chapter 4: Hydraulic Pumps and Motors Overview, 106

4.1- Basic Function of Hydraulic Pumps and Motors, 107

4.2- Classification of Pumps and Motor, 108

4.3- Hydrostatic Versus Hydrodynamic Pumps and Motors, 113

4.3.1- Principles of Operation, 113

4.3.1.1- Positive Displacement Principle of Operation, 113

4.3.1.2- Hydrodynamic Principle of Operation, 115

4.3.2- Synonymous Names, 116

4.3.3- Characteristic Curves, 116

4.3.4- Applications, 117

4.4- Standard Hydraulic Symbols of Pumps and Motors, 118

4.5- Fixed Versus Variable Displacement Pumps and Motors, 120

4.5.1- Functional Comparison, 120

4.5.2- Features of Variable Displacement Pumps and Motors, 122

4.5.3- Controllers for Variable Displacement Pumps and Motors, 123

4.6- Similarity and Differences between Pumps and Motors, 124

4.7- Differences between Pumps and Motors, 124

4.8- Pump and Motor Size Definition, 124

4.9- Pump and Motor Flow Rate Definition, 125

4.10- Positive Displacement Pumps Flow Fluctuation, 126

4.11- Power Distribution in a Hydraulic System, 127

4.12- Power Losses in Pumps and Motors, 129

4.12.1- Matter of Facts, 129

4.12.2- Volumetric Efficiency, 130

4.12.3- Hydro-Mechanical Efficiency, 131

4.12.4- Total Efficiency, 132

4.12.5- Effect of Operating Conditions on Efficiencies, 133

4.12.6- Pump Performance Evaluation Case Study, 135

4.12.7- Motor Performance Evaluation Case Study, 137

4.13- Basic Types of Pumps and Motors, 139

4.14- External Gear Pumps and Motors, 140

- 4.14.1- External Gear Pump, 140
- 4.14.2- External Gear Motor, 146
- 4.14.3- Special Designs: Lobe Pump, 147
- 4.14.4- Special Designs: DUO Pump, 148
- 4.14.5- Special Designs: Helical Gear Pump, 149
- 4.14.6- Special Designs: Silence-Plus Pump, 149
- 4.14.7- Special Designs: Screw Pump, 150

4.15- Internal Gear Pump / Motors, 151

- 4.15.1- Internal Gear Pump, 151
- 4.15.2- External versus Internal Gear Pumps, 152
- 4.15.3- Special Designs: Gerotor Pump and Motor, 152

4.16- Vane Pumps and Motors, 153

- 4.16.1- Fixed Displacement Unbalanced Pumps, 153
- 4.16.2- Fixed Displacement Unbalanced Motors, 159
- 4.16.3- Fixed Displacement Balanced Vane Pumps, 160
- 4.16.4- Fixed Displacement Balanced Motors, 161
- 4.16.5- Variable Displacement Vane Pumps, 162

4.17- Piston Pumps and Motors, 163**4.18- Radial Piston Pump and Motors, 164**

- 4.18.1- Radial Piston Pumps, 164
- 4.18.2- Radial Piston Motors, 166

4.19- Axial Piston Bent-Axis Pumps and Motors, 167

- 4.19.1- Fixed Displacement Bent-Axis Pumps, 167
- 4.19.2- Fixed Displacement Bent-Axis Motors, 169
- 4.19.3- Variable Displacement Bent-Axis Pumps and Motors, 170

4.20- Axial Piston Swash-Plate Pumps and Motors, 171

- 4.20.1- Fixed Displacement Swash-Plate Pumps, 171
- 4.20.2- Special Design: Wobble Plate Pumps, 174
- 4.20.3- Fixed Displacement Swash-Plate Motors, 175

4.20.4- Variable Displacement Swash-Plate Pumps and Motors, 176

4.20.5- Comparison between Swash-Plate and Bent-Axis Mechanisms, 177

4.21- Pump and Motor Selection Criteria, 178

Chapter 5: Hydraulic Valves Overview, 179

5.1- Classification of Hydraulic Valves, 180

5.1.1- Classification of Hydraulic Valves Based on the Control Mission, 181

5.1.2- Classification of Hydraulic Valves Based on the Control Element, 182

5.1.3- Classification of Hydraulic Valves Based on the Valve Actuation, 184

5.1.4- Classification of Hydraulic Valves Based on Valve Operation, 185

5.1.5- Classification of Hydraulic Valves Based on Valve Control Pressure Source, 186

5.1.6- Classification of Hydraulic Valves Based on Valve Control Level, 187

5.1.7- Classification of Hydraulic Valves Based on Valve Mounting Method, 188

5.2- Pressure Control Valves, 189

5.2.1- Pressure Relief Valve, 189

5.2.1.1- Pressure Relief Valves Features and General Functions, 189

5.2.1.2- Construction and Operation of Direct-Operated Pressure Relief Valves, 194

5.2.1.3- Pilot-Operated Pressure Relief Valves, 196

5.2.1.4- Construction and Operation of Pilot-Operated Pressure Relief Valves, 197

5.2.1.5- Pilot-Operated Pressure Relief Valve for Multiple Pressure Settings, 199

5.2.1.6- Pilot Operated Pressure Relief Valve with Pump Unloading Feature, 200

5.2.1.7- Pressure Relief Valve Performance Characteristics, 203

5.2.2- Counterbalance Valve, 205

5.2.2.1- Counterbalance Valves Features and General Functions, 205

5.2.2.2- Construction and Operation of Direct-Operated Counterbalance Valves, 207

5.2.2.3- Construction and Operation of Pilot-Operated Counterbalance Valves, 208

5.2.3- Pressure Sequence Valve, 210

5.2.3.1- Sequence Valves Features and General Functions, 210

5.2.3.2- Construction and Operation of Direct-Operated Sequence Valves, 212

5.2.3.3- Construction and Operation of Pilot-Operated Sequence Valves, 213

- 5.2.4- Pressure Reducing Valve, 215
 - 5.2.4.1- Pressure Reducing Valves Features and General Functions, 215
 - 5.2.4.2- Construction and Operation of Direct-Operated Press. Reducing Valves, 216
 - 5.2.4.3- Construction and Operation of Pilot-Operated Pressure Reducing Valves, 216
- 5.2.5- Unloading Valve, 220
 - 5.2.5.1- Unloading Valves Features and General Functions, 220
 - 5.2.5.2- Construction and Operation of Direct-Operated Unloading Valves, 223
 - 5.2.5.3- Construction and Operation of Pilot-Operated Unloading Valves, 224
 - 5.2.5.4- Unloading Valve versus Pressure Relief Valve with Unloading Feature, 226
- 5.2.6- Over-Center Valve, 227
 - 5.2.6.1- Over-Center Valves Features and General Functions, 227
 - 5.2.6.2- Construction and Operation of Direct-Operated Over-Center Valves, 229
 - 5.2.6.3- Construction and Operation of Pilot-Operated Over-Center Valves, 230
- 5.2.7- Motor Brake Valve, 231
 - 5.2.7.1- Over-Center Valves Features and General Functions, 231
 - 5.2.7.2- Construction and Operation of Direct-Operated Motor Brake Valves, 232
 - 5.2.7.3- Construction and Operation of Pilot-Operated Over-Center Valves, 234
- 5.2.8- Symbols of Pressure Control Valves, 235
- 5.2.9- Pressure Control Valves Function Identification, 237
- 5.3- Directional Control Valves, 238**
 - 5.3.1- Basic Functions of Directional Control Valves, 239
 - 5.3.2- Identification of Linear Spool Type Directional Control Valves, 239
 - 5.3.2.1- Valve Designation, 239
 - 5.3.2.2- Initial Position Location and Naming Conventions, 241
 - 5.3.2.3- Directional Valve Actuation, 244
 - 5.3.2.4- Directional Valve Reset, 248
 - 5.3.2.5- Examples of Directional Valve Identification, 249
 - 5.3.3- Direct-Operated Linear Spool Directional Valves, 250
 - 5.3.3.1- Operating Principle of a 2/2 DCV, 250
 - 5.3.3.2- Operating Principle of a 3/2 DCV, 251

- 5.3.3.3- Operating Principle of a 4/2 DCV, 252
- 5.3.3.4- Operating Principle of a 4/3 DCV, 253
- 5.3.4- Pilot-Operated Linear Spool Directional Valves, 255
 - 5.3.4.1- Why Pilot-Operated Directional Control Valve? 255
 - 5.3.4.2- Construction and Operation Principle of Pilot Op. Directional Valves, 257
- 5.3.5- Performance Curves of Linear Spool Directional Valves, 263
- 5.3.6- Mobile Control Blocks, 263
- 5.3.7- Operation Principle of Rotary Sliding Spool Directional Valves, 265
- 5.3.8- Check Valves, 267
 - 5.3.8.1- Basic Function of Check Valves, 267
 - 5.3.8.2- Applications of Check Valves, 267
 - 5.3.8.3- Construction and Operating Principle of a Direct-Operated Check Valve, 268
 - 5.3.8.4- Construction and Operating Principle of a Pilot-Operated Check Valve, 270
- 5.3.9- Shuttle Valves, 271
- 5.3.10- Shut Off Valves, 272
- 5.4- Flow Control Valves, 273**
 - 5.4.1- Basic Function, 273
 - 5.4.2- Classification of Flow Control Valves, 273
 - 5.4.3- Throttle Valves, 274
 - 5.4.3.1- Operating Principle of Throttle Valves, 274
 - 5.4.3.2- Construction of Throttle Valves, 276
 - 5.4.3.3- Characteristic Curves of Throttle Valves, 277
 - 5.4.4- Flow Regulators, 277
 - 5.4.4.1- Operating Principle of Pressure Compensated Flow Control Valves, 268
 - 5.4.4.2- Construction of Flow Regulators, 281
 - 5.4.4.3- Characteristic Curves of Flow Regulators, 282
 - 5.4.5- Flow Dividers, 283
 - 5.4.5.1- Throttle Type Flow Dividers, 285
 - 5.4.5.2- Motor Type Flow Dividers, 286
 - 5.4.6- Priority Valve, 287

Chapter 6: Hydraulic Reciprocating Actuators, 288

6.1- Reciprocating Hydraulic Actuators, 289

6.2- Hydraulic Cylinders, 290

6.2.1- Applications of Hydraulic Cylinders, 290

6.2.2- Configurations of Hydraulic Cylinders, 291

6.2.3- Single Acting Hydraulic Cylinders, 292

6.2.3.1- Single Acting Spring Return Hydraulic Cylinders, 292

6.2.3.2- Single Acting Load Return Hydraulic Cylinders, 292

6.2.4- Double Acting Hydraulic Cylinders, 293

6.2.4.1- Differential Hydraulic Cylinders, 293

6.2.4.2- Tandem Hydraulic Cylinders, 294

6.2.4.3- Duplex Hydraulic Cylinders, 294

6.2.4.4- Synchronous Hydraulic Cylinders, 295

6.2.5- Hydraulic Rams, 296

6.2.6- Telescopic Hydraulic Cylinders, 297

6.2.7- Cylinders Terminology, 298

6.2.8- Sizing Calculations of a Hydraulic Cylinder, 299

6.2.8.1- Effective Area, 299

6.2.8.2- Pressure Requirements of a Hydraulic Cylinder, 299

6.2.8.3- Flow Requirements of a Hydraulic Cylinder, 300

6.2.8.4- Effect of Area Ratio on Working Pressure, 300

6.2.8.5- Effect of Area Ratio on Working Flow, 302

6.2.8.6- Case Study of Sizing a Hydraulic Cylinder, 302

6.2.9- Body Styles of Hydraulic Cylinders, 303

6.2.9.1- Tie-Rod Cylinders, 303

6.2.9.2- Mill-Type Cylinders, 305

6.2.10- Cylinder Cushioning, 306

6.3-Rotary Actuators, 308

6.3.1- Applications of Rotary Actuators, 308

6.3.2- Configurations of Rotary Actuators, 309

6.3.2.1- Gear Type Rotary Actuators, 310

6.3.2.2- Vane Type Rotary Actuators, 313

6.3.2.3- Piston Type Rotary Actuators, 315

6.3.3- Rotary Actuator Sizing Calculations, 316

6.3.3.1 - Pressure Requirements of a Rotary Actuator, 316

6.3.3.2 - Flow Requirements of a Rotary Actuator, 316

Chapter 7: Hydraulic Accumulators, 317

7.1- Operating Principle of Hydraulic Accumulators, 318

7.2- Hydraulic Accumulators Sizing Calculations, 319

7.3- Construction of Hydraulic Accumulators, 323

7.3.1- Construction of Piston Type Accumulators, 324

7.3.2- Construction of Bladder Type Accumulators, 325

7.3.3- Construction of Diaphragm Type Accumulators, 326

7.4- Applications of Hydraulic Accumulators, 327

7.4.1- Using an Accumulator for Safety Purposes, 327

7.4.2- Using an Accumulator for Energy Saving Purposes, 328

7.4.3- Using an Accumulator as a Hydraulic Spring, 329

Chapter 8: Hydraulic Circuits for Basic Applications, 330

8.1- Safety Considerations in Design of a Hydraulic System, 331

8.1.1- Pressure Limiting, 331

8.1.2- Anti-Cavitation and Load Port Checks, 333

8.2- Energy Saving Considerations in Design of a Hydraulic System, 335

8.2.1- Unloading a Pump that Drives a Single Actuator, 335

8.2.2- Unloading a Pump that Drives Multiple Actuators, 336

8.2.3- Unloading a Pump by a PRV with Unloading Feature, 338

8.2.4- Unloading a Pump by a Pressure Unloading Valve, 339

8.2.5- Unloading a Pump in Mobile Applications, 340

8.3- Motion Control of a Single Actuator, 342

8.3.1- Motion Control of a Single Actuator against a Resistive Load, 343

8.3.1.1- Motion Control of a Single Acting Cylinder, 343

8.3.1.2- Motion Control of a Unidirectional Motor, 348

8.3.1.3- Motion Control of a Double Acting Cylinder, 351

8.3.1.4- Motion Control of a Bidirectional Motor, 352

8.3.1.5- Motion Control of a Rotary Actuator, 354

8.3.2- Motion Control of a Single Actuator against a Combined Load, 355

8.3.3- Motion Control of a Single Actuator against an Over-Center Load, 360

8.4- Motion Control of Multiple Actuators in Industrial Applications, 363

8.4.1- Motion Control of Multiple Actuators Connected in Parallel, 363

8.4.1.1- Motion Control of Multiple Cylinders in Parallel, 363

8.4.1.2- Motion Control of Multiple Motors Connected in Parallel, 365

8.4.2- Motion Control of Multiple Actuators Connected in Series, 366

8.4.2.1- Motion Control of Multiple Cylinders in Series, 367

8.4.2.2- Motion Control of Multiple Motors in Series, 371

8.5- Motion Control of Multiple Actuators in Mobile Applications, 374

8.5.1- Parallel Control Blocks in Mobile Machines, 374

8.5.2- Tandem Control Blocks in Mobile Machines, 376

8.5.3- Combined Control Blocks in Mobile Machines, 377

8.5.4- Series Control Blocks in Mobile Machines, 377

8.6- Control Block Actuation, 379

8.6.1- Manual Actuation of Control Blocks, 379

8.6.2- Hydraulic Actuation of Control Blocks, 380

8.6.3- Electric Actuation of Control Blocks, 386

8.7- Speed Control of a Hydraulic Actuator, 387

8.7.1- Valve-Controlled Actuators versus Pump-Controlled Actuators, 387

8.7.2- Bypass (Bleed-off) Speed Control, 389

8.7.3- Meter-In Speed Control, 390

8.7.4- Meter-Out Speed Control, 391

8.7.5- Speed Control Comparative Study, 392

8.7.6- Placement of the Flow Control Valve versus the Directional Control Valve, 392

8.8- Boosting the Speed of a Hydraulic Actuator, 395

8.8.1- Regenerative Circuit for Boosting the Extension Speed of a Differential Cylinder, 395

8.8.1.1- Effect of the Regenerative Connection on the Operating Speed, 396

8.8.1.2- Effect of the Regenerative Connection on the Operating Pressure, 399

8.8.2- Boosting an Actuator Speed by an Accumulator, 399

8.9- Energy Storage Application, 401

8.10- Actuators Synchronization Application, 402

8.11- Cylinder Deceleration Application, 405

8.12- Sequence Control Application, 406

8.13- Hydrostatic Transmission, 408

APPENDIXES, 410

APPENDIX A: LIST OF FIGURES, 410

APPENDIX B: LIST OF TABLES, 424

APPENDIX C: SOFTWARE: HYDRAULIC COMPONENT SIZING CALCULATOR, 425

APPENDIX D: LIST OF ANIMATED CIRCUITS (AUTOMATION STUDIO), 425

APPENDIX E: LIST OF REFERENCES, 428

INDEX, 437

PREFACE

An unfair question being asked that is: “Which of the Mechanical, Electrical and Fluid Power systems is the best for power transmission and control?” The fact is none of these systems is the best from all points of view. If one of these systems is best from all points of view, why would the other systems still be in use? What we can agree about is that there is a specific system that is the best choice for a specific application.

This book is intended for industry professionals who would like to achieve a deeper understanding of the principles of hydraulic control, and who would like to improve their practical skills in building a hydraulic-driven machine. Unlike similar books, the contents of this book are presented in a unique way. It fills the gap between the very academic style of fluid power books and the very commercial style of books that are produced by fluid power manufacturers.

The book contains two software packages to download. The first package is the *Hydraulic Components Sizing Calculator*. The second package is the *Animated Circuits Files*, which is produced by Automation Studio Software. Both packages are extremely helpful in understanding the subject and interactive designing of a hydraulic system.

Hydraulic system builders and users will find this book beneficial in understanding the operating principles of the hydraulic components, using the right terminologies, determining the proper specifications of a hydraulic component, performing the required calculations to size a hydraulic component, reading the hydraulic schematics, and much more.

With more than twenty-five years of experience in teaching fluid power for industry professionals, the author had effectively applied his solid understanding to the subject and his post-doctoral level of academic education in the preparation of this book. Half of this book has been written while I am flying from one state to other to conduct a seminar. The book features in brief are easy language, brand non-biased, practical oriented, associated with a workbook, colored, and demonstrative.

The author wants to continue on his goal of supporting fluid power and motion control professional education by developing the following series of volumes:

- Hydraulic Systems Volume 1: Introduction to Hydraulics for Industry Professionals.
- Hydraulic Systems Volume 2: Electro-Hydraulic Components and Systems.
- Hydraulic Systems Volume 3: Hydraulic Fluids and Contamination Control.
- Hydraulic Systems Volume 4: Hydraulic Fluids Conditioning.
- Hydraulic Systems Volume 5: Best Practices for Safety and Maintenance.
- Hydraulic Systems Volume 6: Troubleshooting and Failure Analysis.
- Hydraulic Systems Volume 7: Hydraulic Systems Modeling and Simulation for Application Engineers.
- Hydraulic Systems Volume 8: Design Strategies of Hydraulic Systems.
- Hydraulic Systems Volume 9: Design Strategies of Electro-Hydraulic Systems.
- Hydraulic Systems Volume 10: Hydraulic Components Modeling and Simulation.

ACKNOWLEDGEMENT

First of all I would like to thank the almighty Allah who gave me the wealth of knowledge, the health, and the will to complete this work.

To my head's crown, my wife, Nahla Mohamed

To my sons, Karim, Sharif, Moataz and Yasser

To the soul of my parents who taught me the values of ISLAM

To my best teachers and supervisors: Dr. Saad Kassem, Dr. Rama Bhat, Dr. Ibrahim Saleh, Dr. Galal Rabie, and Dr. Abed Kattab

To friends who were always supportive: Eng. Yasser Fahmy and Eng. Ashraf Omar

The author wishes to thank:

- *Mr. Thomas Wanke, the Director of Fluid Power Institute at MSOE, for his effective effort in reviewing the presented technical information.*
- *Dr. James Mallmann for his considerable efforts in reviewing the language of the text.*
- *These companies, BOSCH REXROTH and ASSOFLUID, who permitted use some of their copyrighted pictures to make this book more demonstrative.*

Lastly, the author particularly wishes to thank the administration at Milwaukee School of Engineering and his supervisors who made his job easy to develop this book.

ABOUT THE BOOK

Book Description:

Introduction to Hydraulics for Industry Professionals is a learning package for students and professionals who are looking to build their fluid power careers. The package includes a *colored textbook*, an *interactive software-based tool to size hydraulic components*, *electronic files for the animated hydraulic circuits*, and a *colored workbook* (separate price) that contains printed power point slides, chapter reviews and assignments. The book is the first in a series that the author plans to publish to offer complete and comprehensive teaching and design tools for the fluid power industry. This book is an attempt to fill the gap between the very academic style of fluid power books and the very commercial style of books that are produced by fluid power manufacturers. The book presents the equations in both the Metric and English systems of units. The book considers presenting real-life examples for Mobile and Industrial applications. The book goes above and beyond the fundamental level of fluid power. This book covers the construction and operating principles of the hydraulic components, using the right terminologies. Topics covered include: determination of proper specifications of hydraulic components, how to perform the required calculations to size a hydraulic component, how to read hydraulic schematic diagrams, how to predict pump efficiency under specific operating conditions, how to draw the power distribution for the duty cycle of a machine, how to investigate the losses in a hydraulic system, a presentation of different concepts for building hydraulic circuits, and much more.

The textbook is produced in letter size (8.5 x 11) inches, and weighs 3.5 lb. The textbook contains a total of eight chapters distributed on 337 pages. The workbook is produced in the same size and weighs 1 lb. The associated software is online downloadable.

Book Objectives:

Chapter 1: Hydraulic Systems Overview

This chapter presents a comparative study of different power transmission and control systems; namely: Mechanical, Electrical, Hydraulic and Pneumatic. This chapter explains the main features of hydraulic systems and concludes by exploring the structure of a generic hydraulic system.

Chapter 2: Basic Concepts Review

This chapter presents reviews of fundamental concepts of multidisciplinary systems; namely: Mechanics, Physics, Fluid Mechanics and Hydraulics. The fundamental concepts reviewed are the ones that are useful in understanding some properties of hydraulic systems. In reviewing the concepts of fluid mechanics, this chapter explains how to quantify the frictional and local pressure losses in a hydraulic line based on laminar or turbulent flow patterns in the line.

Chapter 3: Hydraulic Component Sizing Calculations

This chapter presents a case study to demonstrate the method to size a hydraulic system to achieve desired operating conditions. The chapter presents the step-by-step procedure to perform the calculations required to size the components in the system.

Chapter 4: Hydraulic Pumps and Motors Overview

This chapter has three main parts. The first part presents an overview of: positive displacement machines versus hydrodynamic machines, pumps versus motor mechanisms, fixed versus variable displacement machines, and symbols. The second part focuses on investigating the power losses in pumps and motors. This investigation is used to evaluate the efficiency of a pump and a motor under certain operating conditions using data published by the manufacturers. The third part of the chapter presents the construction and operating principles of gear, vane, and piston type positive displacement machines. The chapter concludes by the selection criteria for pumps and motors.

Chapter 5: Hydraulic Valves Overview

This chapter presents the construction and operating principles of the three families of control valves: namely pressure, directional, and flow control valves. The chapter presents the reasons why one of these valves should be selected over the other from a practical point of view. Valve symbols and comparison tables are presented.

Chapter 6: Hydraulic Reciprocating Actuators

This chapter covers two types of hydraulic reciprocating actuators; namely cylinders and rotary actuators. The chapter presents the various types of hydraulic cylinders, the effect of using a differential cylinder on the pressure and flow distribution in the system, and the calculations for sizing a hydraulic cylinder. The chapter also presents the various types of rotary actuators and the reasons for using them. Symbols for reciprocating actuators are presented.

Chapter 7: Hydraulic Accumulators

This chapter covers the construction, operating principles and symbols of the three types of accumulators: piston, bladder and diaphragm type. The chapter discusses the applications of energy storage and shock absorption using accumulators.

Chapter 8: Hydraulic Circuits for Basic Applications

This chapter covers the basic safety and energy saving requirements of a hydraulic system. The chapter also presents ideas for motion control of a single hydraulic actuator against resistive and overrunning loads, multiple hydraulic actuators in parallel and series, speed control of a hydraulic actuator, boosting speed of a hydraulic actuator, sequence of operation, and hydrostatic transmission.

Book Statistics:

The table shown below contains interesting statistical data about the textbook:

<i>Chapter #</i>	<i>Pages</i>	<i>Figures</i>	<i>Animated Circuits</i>	<i>Equations</i>	<i>Tables</i>	<i>Lines</i>	<i>Words</i>	<i>Characters</i>
<i>Chapter 1</i>	26	22	2	0	10	820	5323	28392
<i>Chapter 2</i>	50	50	3	37	4	1450	9359	46113
<i>Chapter 3</i>	9	10	0	0	0	277	1836	9305
<i>Chapter 4</i>	72	86	4	20	2	1697	14197	71407
<i>Chapter 5</i>	108	125	23	0	5	2205	15918	79222
<i>Chapter 6</i>	29	26	1	8	1	604	3869	19573
<i>Chapter 7</i>	13	8	0	4	1	435	2048	9869
<i>Chapter 8</i>	80	89	46	7	4	1492	9985	51416
<i>Other</i>	99	-	-	-	-	-	-	-
<i>Total</i>	436	416	79	76	27	8980	62535	315297

ABOUT THE AUTHOR



Medhat Khalil, Ph.D., Director of Professional Education & Research Development at the Applied Technology Center, Milwaukee School of Engineering, Milwaukee, WI, USA. Medhat got his bachelor's degree in mechanical engineering from Military Technical College (MTC), Cairo, Egypt. He got his master's degree in Mechanical Engineering from Cairo University, Cairo, Egypt. Medhat has been granted his Ph.D. in Mechanical Engineering and Post-Doctoral Industrial Research Fellowship from Concordia University in Montreal, Quebec, Canada. Medhat, so far, published three textbooks. Medhat participated in many technical conferences and published several reviewed technical papers and he is in the process of registering number of patents. Medhat has been certified by the International Fluid Power Society (IFPS) as: Certified Fluid Power Hydraulic Specialist (CFPHS) and Certified Fluid Power Accredited Instructor (CFPAI). Medhat is a member of many

grand institutions such as Center for Compact and Efficient Fluid Power Engineering Research Center (CCEFP), listed Fluid Power Consultant by the National Fluid Power Association (NFPA), and listed professional instructor by the American Society of Mechanical Engineers (ASME) and National American Die Casting Association (NADCA). Medhat has been assigned as the chair of the education committee for the International Fluid Power Exposition (IFPE2017 and 2020). Medhat developed and taught various courses for industry professionals. Medhat has a balanced academic and industrial experience. Medhat has a deep working experience in the field of Mechanical Engineering; more specifically in fluid power and motion control. Medhat had worked for several world-wide recognized industrial organizations such as Rexroth in Germany and CAE in Canada.

Medhat had designed several hydraulic systems and developed several analytical and educational software. Medhat also has vast experience in modeling and simulation of dynamic systems using Matlab-Simulink. Medhat was the designer and founder of the Universal Fluid Power Trainers. Medhat was the recipient of the "Otto Maha Pioneers in Fluid Power" award by 2012.

