FLUID POWER
Generation, Transmission and Control

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Preface

We have written this book for students and engineers in mechanical, production, automobile, and mechatronics engineering who wish to understand fluid power science and apply it in solving the engineering problems. This book is primarily designed for the use of graduate and postgraduate students, as well as students who are preparing for AMIE and various other competitive examinations. For the practicing engineers, it is hoped that this book will be a very useful reference of collected information that will assist in the solution of many problems encountered in the application of fluid power in the industry.

We have endeavored to present the subject in a simple and rational way. In preparation of this book, we have taken advantage of the vast experience gained in the course of our work during the last 30 years. It has been our aim to show the basic principles underlying fluid power by means of providing typical examples. Empirical formulae have been used only when it is not practical to use mathematical analysis. It has been our experience that a sound knowledge of mechanics of fluid is very essential to take up the study of Fluid Power Control and Design. It is expected that the students using this book have completed a course in applied mathematics.

The main objective of writing this book has been to give a clear understanding of the concepts underlying fluid power control. We have strived to teach the subject on a scientific basis, to maintain the physical perceptions in the various derivations and to give the short comprehending solution to a variety of complex problems. The parameters kept in mind while writing the book are coverage of contents to suit syllabi of various Indian Universities, prerequisite knowledge of the user of this book, lucidity of writing, clarity of thoughts and variety of solved and unsolved numerical problems, including problems from competitive examinations.

Despite the importance and relevance of the subject, it is observed that the subject has not been given its justified importance in the undergraduate engineering course curriculum of Indian Technical Institutes. In most cases, the subject has been taught as an elective course. In almost all cases, the subject has been set aside for advanced reading in the postgraduate section. We feel that the subject should be a separate one in the undergraduate level, where fundamentals of physics of fluid power control should be taught with great care and with sufficient mathematical exposure.

Organization of the Book

The 21 self-contained chapters in this book have been systematically organized as follows:

1. **Chapter 1**: This chapter gives a brief introduction to the fluid power industry and then develops the basic concepts for power delivery with fluids. Elementary hydraulic and pneumatic circuit components have been presented along with their advantages and disadvantages.
2. **Chapter 2**: This chapter contains an outline of corpuscular aspects of fluid mechanics and some practical applications.
3. **Chapter 3**: This chapter introduces us to properties and functions of hydraulic fluids normally used in the industry. The primary aspect of this chapter is the determination of properties of fluid. Now the industry has begun to consider the use of less mineral oil content as both supply and environmental issues have started dominating many new applications.
4. **Chapter 4**: This chapter discusses the various governing laws used in fluid power. Students should focus on chapters 2, 3 and 4, as the success of future study depends on these chapters.
5. **Chapter 5**: This chapter deals with various fittings used in fluid power systems. The guidelines to select pipes, hoses and tubings have been discussed in this chapter.
6. **Chapter 6**: In this chapter, various energy losses have been discussed in great detail. It also contains design problems containing all kinds of losses.
7. **Chapter 7**: This chapter discusses the various pumps used in fluid power industries.
8. **Chapters 8 and 9**: These two chapters complement Chapter 7 and are all about the interaction between hydraulic actuators and hydraulic motors.
9. **Chapter 10**: This chapter introduces hyrdostatic transmission systems.
10. **Chapter 11 to Chapter 13**: These chapters introduce various control valves to control direction, pressure and flow.
11. **Chapter 14**: This chapter describes the various circuits and control methods and also the various methods of controlling hydraulic actuators.
12. **Chapter 15:** This chapter involves a more detailed mathematical treatment of a wider range of flow control valves.

13. **Chapter 16:** This chapter presents the linear analysis of the hydraulic systems and servo mechanism.

14. **Chapters 17 and 18:** These chapters deal with proportional control valves and servo valves. In both the chapters, the mechanical aspects of valves, the valve actuation mechanisms and valve performance have been discussed.

15. **Chapter 19:** This chapter is concerned with the storing of fluid energy using accumulators.

16. **Chapter 20:** Characteristics of auxiliary components used in fluid power have been covered in this chapter.

17. **Chapter 21:** This chapter deals with the maintenance of fluid power systems.

Apart from all these, each chapter contains Multiple-Choice Questions, Review Questions, Exercises, Solved Examples, and Frequently Asked Questions of various Indian universities’ examinations (Short-Answer Type). Presentation of the subject in SI units and simple language makes the book useful for effective teaching and application.

### Salient Features of the Book

1. Presentation of basic theory in simple and readily understandable form.
2. A balanced presentation of mathematical and concept approaches.
3. Large number of solved problems and unsolved problems picked up from various Indian technical institutes and universities.
4. Each chapter has a concise and comprehensive treatment of topics with strong emphasis on fundamental concepts. A number of theoretical questions and unsolved exercises have been given for practice so as to widen the horizon of comprehension of the topic.

### Guidelines for Instructors

This book has been written as textbook for one-semester course in fluid power. It is expected that the course will be taught to undergraduate and graduate students. In most engineering curricula, fluid power control is an elective course. Students interested in machine design, mechatronics, automobile, manufacturing and production engineering make room in their course of study.

We have found that 10 problems in 1 week is an ample assignment. Certain problems can be assigned to the students as the take-home assignment to solve them using MATLAB.

This book is supplemented with solution manual for each chapter. Solution manual contains answers for Review questions and detailed solutions to Exercise problems given at the end of each chapter. This is available on request for instructors. Kindly mail to acadmktg@wiley.com

### Guidelines for Students

Mathematics is intimately concerned with the study of Fluid Power. In order to study the characteristics of fluid power systems, students have to resort to understanding the physical meaning and modeling of the system and write the characteristic equations. To solve the fluid power problems by MATLAB, knowledge of matrix algebra is essential. Good knowledge of fluid mechanics is also very much essential to derive full benefit from this textbook.

Although every care has been taken in correcting proofs and checking numerical examples, errors may be present and further suggestions to improve upon remain. We will be highly grateful to the readers for any feedback. Please send your feedback to Jagdishsg@nitc.ac.in

Jagadeesha T.
Thammaiah Gowda
This book took almost a decade in its making. During that period, a multitude of friends, clients, and associates have provided us with support, helped us solidify our ideas regarding the fluid power control theory. We remain ever grateful to all of them. We wish to place on record our deep sense of gratitude to our teachers, our parents and our families for encouraging us to pursue an academic career.

Jagadeesha T. would specifically like to thank his wonderful wife Vasanthi and his son Ramkumar for their love, patience and endless sacrifices. He would also like to thank his sister Prabhavathi T., without whose presence, encouragement and comfort, this textbook would have remained merely a good intention. Acknowledgements are due to several of his close associates and team leaders in India and abroad. These include: Ashok Kumar, Head (Operations), Yogesh Kale, Head (Design) of Harith Grammer (TVS-Suzuki Group), Hosur; Louis Kim, Head (Thin films), Chartered Semiconductor Manufacturing Ltd., Singapore; Guruvaiah, Head (Controls), Shiv Kumar, Head (Fluid power), Trivedi, Head (Machine design) of TELCO, Pune; Ricky Tan, Director (Automation), Md. Johari, Head (Tooling) of IBM Singapore Pvt. Ltd.; N. Sreekanth, Head (CAD/CAM), Kenny Kwan, Head (R&D) of ASM Technologies, Singapore; Joseph Ong, Head (CVD), Stanley Teo, Head (PVD) of ST Microelectronics, Singapore; James Lee, Director (Operations), Melvin Leo, Staff Engineer (Applications), APP Systems and Services, Singapore; Young Yee, Staff engineer (Process), Applied Materials, Korea; Young Yap, Director (Process), Applied Materials, Singapore; Ganesan, Staff Engineer (Equipment), Infineon, Malaysia.

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It takes a team of many people and lots of hard work to create a quality textbook. Thanks most certainly to Wiley India for publishing this book in a short period. Many thanks to Mr. Praveen Settigere (Sr. Manager Acquisitions, Wiley India) who set the tone for excellence and who provided the vision and leadership to create such a quality product. Thanks are also to Ms. Meenakshi Sehrawat (Executive Editor, Wiley India) and Mr. Rupnarayan Das (Associate Editor, Wiley India) who worked long hours to improve our prose and produce this text from the first page of the manuscript to the final, bound product. We would also like to thank Mr. Rakesh Poddar (Production Editor, Wiley India) for meticulously managing the production-related jobs.
## Nomenclature

### Table 1 | English alphabets

<table>
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<th>Letter</th>
<th>Description</th>
<th>Symbol</th>
<th>Unit/Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>a</td>
<td>Acceleration, m/s²</td>
<td>p</td>
<td>Pressure, MPa</td>
</tr>
<tr>
<td>A</td>
<td>Area in m²</td>
<td>p&lt;sub&gt;piston&lt;/sub&gt;</td>
<td>Pressure on piston, MPa</td>
</tr>
<tr>
<td>A&lt;sub&gt;rod&lt;/sub&gt;</td>
<td>Area of rod in m²</td>
<td>p&lt;sub&gt;rod&lt;/sub&gt;</td>
<td>Pressure on rod, MPa</td>
</tr>
<tr>
<td>A&lt;sub&gt;piston&lt;/sub&gt;</td>
<td>Area of piston in m²</td>
<td>p&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Inlet pressure, MPa</td>
</tr>
<tr>
<td>A&lt;sub&gt;annulus&lt;/sub&gt;</td>
<td>Area of annulus in m²</td>
<td>p&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Outlet pressure, MPa</td>
</tr>
<tr>
<td>A&lt;sub&gt;inlet&lt;/sub&gt;</td>
<td>Area at inlet, m²</td>
<td>q</td>
<td>Flow rate in LPm or m³/s</td>
</tr>
<tr>
<td>A&lt;sub&gt;outlet&lt;/sub&gt;</td>
<td>Area at outlet, m²</td>
<td>q</td>
<td>Flow rate through valve in LPm or m³/s</td>
</tr>
<tr>
<td>A&lt;sub&gt;v&lt;/sub&gt;</td>
<td>Area of valve in m²</td>
<td>Δp</td>
<td>Pressure drop in bar, or Pa</td>
</tr>
<tr>
<td>B</td>
<td>Thickness of gear, m</td>
<td>Δp&lt;sub&gt;p&lt;/sub&gt;</td>
<td>Pressure drop across pump, Pa</td>
</tr>
<tr>
<td>c</td>
<td>Radial clearance</td>
<td>Δp&lt;sub&gt;m&lt;/sub&gt;</td>
<td>Pressure drop across motor, Pa</td>
</tr>
<tr>
<td>C&lt;sub&gt;d&lt;/sub&gt;</td>
<td>Coefficient of discharge</td>
<td>R&lt;sub&gt;r&lt;/sub&gt;</td>
<td>Outer radius of output shaft, m</td>
</tr>
<tr>
<td>C&lt;sub&gt;p&lt;/sub&gt;</td>
<td>Specific heat, W/kg °C</td>
<td>R&lt;sub&gt;v&lt;/sub&gt;</td>
<td>Outer radius of vane, m</td>
</tr>
<tr>
<td>D</td>
<td>Diameter of piston, m</td>
<td>Re</td>
<td>Reynolds number, dimensionless</td>
</tr>
<tr>
<td>D&lt;sub&gt;p&lt;/sub&gt;</td>
<td>Diameter of pipe, m</td>
<td>S</td>
<td>Stroke, s</td>
</tr>
<tr>
<td>D&lt;sub&gt;i&lt;/sub&gt;</td>
<td>Inside diameter, m</td>
<td>S</td>
<td>Stroke length of piston pumps, m</td>
</tr>
<tr>
<td>D&lt;sub&gt;o&lt;/sub&gt;</td>
<td>Outside diameter, m</td>
<td>T</td>
<td>Time, s</td>
</tr>
<tr>
<td>D&lt;sub&gt;k&lt;/sub&gt;</td>
<td>Diameter of ring of vane pump, m</td>
<td>T&lt;sub&gt;c&lt;/sub&gt;</td>
<td>Time constant, s</td>
</tr>
<tr>
<td>D&lt;sub&gt;c&lt;/sub&gt;</td>
<td>Diameter of cam ring of vane pump, m</td>
<td>T&lt;sub&gt;q&lt;/sub&gt;</td>
<td>Torque, Nm</td>
</tr>
<tr>
<td>d</td>
<td>Diameter of rod, m</td>
<td>T&lt;sub&gt;A&lt;/sub&gt;</td>
<td>Actual torque, Nm</td>
</tr>
<tr>
<td>E</td>
<td>Voltage drop, V</td>
<td>T&lt;sub&gt;T&lt;/sub&gt;</td>
<td>Theoretical torque, Nm</td>
</tr>
<tr>
<td>E&lt;sub&gt;total&lt;/sub&gt;</td>
<td>Total energy, J</td>
<td>V&lt;sub&gt;D&lt;/sub&gt;</td>
<td>Displacement volume, m³</td>
</tr>
<tr>
<td>F</td>
<td>Force applied, N</td>
<td>V&lt;sub&gt;in&lt;/sub&gt;</td>
<td>Inlet volume, m³</td>
</tr>
<tr>
<td>F&lt;sub&gt;inlet&lt;/sub&gt;</td>
<td>Force at inlet, N</td>
<td>V&lt;sub&gt;out&lt;/sub&gt;</td>
<td>Outlet volume, m³</td>
</tr>
<tr>
<td>F&lt;sub&gt;outlet&lt;/sub&gt;</td>
<td>Force at outlet, N</td>
<td>ΔV</td>
<td>Change in volume, m³</td>
</tr>
<tr>
<td>G</td>
<td>Gain</td>
<td>v&lt;sub&gt;1&lt;/sub&gt;</td>
<td>Inlet velocity, m/s</td>
</tr>
<tr>
<td>H</td>
<td>Head of fluid in m</td>
<td>v&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Outlet velocity, m/s</td>
</tr>
<tr>
<td>H&lt;sub&gt;p&lt;/sub&gt;</td>
<td>Energy input to pump, J</td>
<td>v&lt;sub&gt;forward&lt;/sub&gt;</td>
<td>Forward velocity of actuator, m/s</td>
</tr>
<tr>
<td>H&lt;sub&gt;m&lt;/sub&gt;</td>
<td>Energy output from motor, J</td>
<td>v&lt;sub&gt;ret&lt;/sub&gt;</td>
<td>Retraction velocity of actuator, m/s</td>
</tr>
<tr>
<td>H&lt;sub&gt;L&lt;/sub&gt;</td>
<td>Energy loss due to friction, J</td>
<td>Z</td>
<td>No. of pistons in piston pumps</td>
</tr>
<tr>
<td>I</td>
<td>Current, A</td>
<td>Z&lt;sub&gt;1&lt;/sub&gt;</td>
<td>Elevation at inlet, m</td>
</tr>
<tr>
<td>I&lt;sub&gt;h&lt;/sub&gt;</td>
<td>Length of pipe</td>
<td>Z&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Elevation at outlet</td>
</tr>
<tr>
<td>K</td>
<td>Roughness factor</td>
<td>X</td>
<td>Horizontal displacement, m</td>
</tr>
<tr>
<td>K&lt;sub&gt;1&lt;/sub&gt;</td>
<td>Ratio of outside diameter to inside diameter of pipe</td>
<td>Y</td>
<td>Vertical displacement, m</td>
</tr>
<tr>
<td>L</td>
<td>Width of gear teeth, m</td>
<td>Y</td>
<td>No. of pistons in piston pumps</td>
</tr>
<tr>
<td>M</td>
<td>Module of gear, m</td>
<td>Z</td>
<td>Elevation in, m</td>
</tr>
<tr>
<td>n</td>
<td>Revolution per second (RPS)</td>
<td>Z&lt;sub&gt;1&lt;/sub&gt;</td>
<td>Elevation at inlet, m</td>
</tr>
<tr>
<td>N</td>
<td>Revolution per minute (RPM)</td>
<td>Z&lt;sub&gt;2&lt;/sub&gt;</td>
<td>Elevation at outlet</td>
</tr>
<tr>
<td>P</td>
<td>Power, W</td>
<td></td>
<td></td>
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</table>
### Table 2  |  Greek alphabets

<table>
<thead>
<tr>
<th>Symbol</th>
<th>Description</th>
<th>Symbol</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\alpha$</td>
<td>Pressure angle of gear</td>
<td>$\omega$</td>
<td>Angular velocity, rad/s</td>
</tr>
<tr>
<td>$\beta$</td>
<td>Bulk modulus, MPa</td>
<td>$\omega_n$</td>
<td>Natural frequency, Hz</td>
</tr>
<tr>
<td>$\beta_e$</td>
<td>Effective bulk modulus, MPa</td>
<td>$\eta$</td>
<td>Efficiency, %</td>
</tr>
<tr>
<td>$\mu$</td>
<td>Absolute viscosity, cP</td>
<td>$\eta_m$</td>
<td>Mechanical Efficiency, %</td>
</tr>
<tr>
<td>$\nu$</td>
<td>Kinematic viscosity, cSt</td>
<td>$\eta_m^m$</td>
<td>Mechanical Efficiency of motor, %</td>
</tr>
<tr>
<td>$\rho$</td>
<td>Mass density, $\eta_p^m$</td>
<td></td>
<td>Mechanical Efficiency of pump, %</td>
</tr>
<tr>
<td>$\rho_{\text{oil}}$</td>
<td>Mass density of oil</td>
<td>$\eta_o$</td>
<td>Overall efficiency, %</td>
</tr>
<tr>
<td>$\rho_{\text{air}}$</td>
<td>Mass density of air</td>
<td>$\theta$</td>
<td>Inclination of lever, deg</td>
</tr>
<tr>
<td>$\rho_{\text{water}}$</td>
<td>Mass density of water</td>
<td>$\theta_1$</td>
<td>Inlet temperature, °C</td>
</tr>
<tr>
<td>$\rho_{\text{mercury}}$</td>
<td>Mass density of mercury</td>
<td>$\theta_2$</td>
<td>Outlet temperature, °C</td>
</tr>
<tr>
<td>$\gamma$</td>
<td>Specific weight</td>
<td>$\epsilon$</td>
<td>Damping ratio</td>
</tr>
<tr>
<td>$\gamma_{\text{oil}}$</td>
<td>Specific weight of oil</td>
<td>$\delta$</td>
<td>Logarithmic decrement, m</td>
</tr>
<tr>
<td>$\gamma_{\text{water}}$</td>
<td>Specific weight of water</td>
<td>$\mu m$</td>
<td>Micron</td>
</tr>
<tr>
<td>$\tau$</td>
<td>Shear stress, MPa</td>
<td>$\phi$</td>
<td>Inclination of cylinder</td>
</tr>
<tr>
<td>$\sigma$</td>
<td>Tensile stress, MPa</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

### Table 3  |  Abbreviations

<table>
<thead>
<tr>
<th>Abbreviation</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNC</td>
<td>Computer numerically controlled</td>
</tr>
<tr>
<td>NC</td>
<td>Normally closed</td>
</tr>
<tr>
<td>NO</td>
<td>Normally open</td>
</tr>
<tr>
<td>FCV</td>
<td>Flow control valve</td>
</tr>
<tr>
<td>DCV</td>
<td>Direction control valve</td>
</tr>
<tr>
<td>PRV</td>
<td>Pressure relief valve</td>
</tr>
<tr>
<td>CF</td>
<td>Coefficient of friction</td>
</tr>
<tr>
<td>dB</td>
<td>decibel</td>
</tr>
<tr>
<td>HP</td>
<td>Horse power, HP</td>
</tr>
<tr>
<td>SV</td>
<td>Specific volume, m$^3$/kg</td>
</tr>
<tr>
<td>SG</td>
<td>Specific gravity</td>
</tr>
<tr>
<td>KE</td>
<td>Kinetic energy, J</td>
</tr>
<tr>
<td>PE</td>
<td>Potential energy, J</td>
</tr>
<tr>
<td>VI</td>
<td>Viscosity index</td>
</tr>
<tr>
<td>VG</td>
<td>Viscosity grade</td>
</tr>
<tr>
<td>OD</td>
<td>Outer diameter, m</td>
</tr>
<tr>
<td>ID</td>
<td>Inner diameter, m</td>
</tr>
<tr>
<td>FOS</td>
<td>Factor of safety</td>
</tr>
<tr>
<td>WP</td>
<td>Working pressure of hose, MPa</td>
</tr>
<tr>
<td>TF</td>
<td>Transfer function</td>
</tr>
<tr>
<td>BP</td>
<td>Burst pressure of hose, MPa</td>
</tr>
<tr>
<td>HGR</td>
<td>Heat generation rate, W</td>
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