

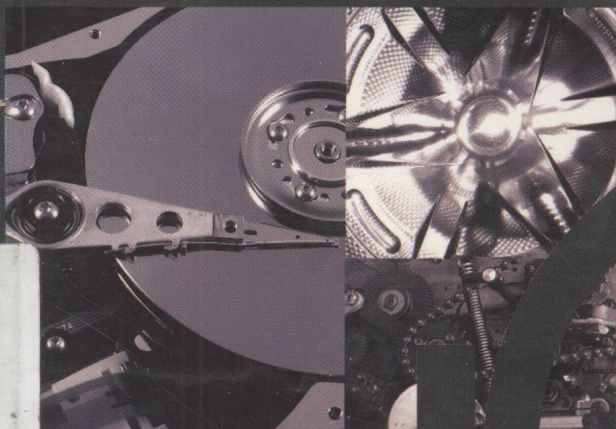
The **McGraw-Hill** Companies

Mechanical Engineering Series

THEORY OF MACHINES

SECOND EDITION

S S RATTAN



THEORY OF MACHINES

SECOND EDITION

S S Rattan

Department of Mechanical Engineering

National Institute of Technology

Kurukshetra



Tata McGraw-Hill Publishing Company Limited

NEW DELHI

McGraw-Hill Offices

New Delhi New York St Louis San Francisco Auckland Bogotá
Caracas Kuala Lumpur Lisbon London Madrid Mexico City Milan
Montreal San Juan Santiago Singapore Sydney Tokyo Toronto

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



Tata McGraw-Hill

Copyright © 2005, 1993, by Tata McGraw-Hill Publishing Company Limited.

Fourth reprint 2006

DRLARRAKRADZC

No part of this publication may be reproduced or distributed in any form or by any means, electronic, mechanical, photocopying, recording, or otherwise or stored in a database or retrieval system without the prior written permission of the publishers. The program listings (if any) may be entered, stored and executed in a computer system, but they may not be reproduced for publication.

This edition can be exported from India only by the publishers,
Tata McGraw-Hill Publishing Company Limited.

ISBN 0-07-059120-2

Published by the Tata McGraw-Hill Publishing Company Limited,
7 West Patel Nagar, New Delhi 110 008, typeset in Times New Roman at
The Composers, 260, C.A.Apt., Paschim Vihar, New Delhi 110 063 and
printed at Adarsh Printers, C51 Mohan Park, Naveen Shahdara, Delhi 110 032.

Cover printer: Rashtriya Printers

The McGraw-Hill Companies

THEORY OF MACHINES

SECOND EDITION

About the Author

S S Rattan is currently Assistant Professor in the Department of Mechanical Engineering at the National Institute of Technology, Kurukshetra. He did his postgraduation in Mechanical Engineering from Punjab Engineering College, Chandigarh in 1981. Since then he has been engaged in teaching and research. He obtained his Ph. D. degree from Kurukshetra University in 1995. He has authored several research papers, which have been published in national and international journals as well as in the proceedings of conferences in India and abroad. He is also the author of another book titled *Fluid Mechanics and Fluid Machines*. He is a member of the Indian Society of Theoretical and Applied Mechanics.

*To the memory of
My Father*

Preface to the Second Edition

The first edition of the book with twenty four reprints spoke volumes of its success and was certainly an index of its popularity among the teaching and student community. However, knowledge never ceases to expand and there is always scope for improvement. The first edition aimed at providing the subject matter in a concise, lucid and simple manner for easy comprehension by all. However, in order to make the book more purposeful and acceptable to a wider section of users, the revised edition includes elegant methods involving vector and complex numbers usually preferred by those who excel in mathematical skills. Such methods frequently lead to computer-aided solutions of the problems. However, those who do not wish to adopt these methods can easily skip them while reading the book.

In the present edition, apart from rewriting some of the previous sections, several new sections have been added in almost all the chapters. Many new worked examples have been incorporated. The computer programs have been rewritten in *C*, the most widely used language today. Theoretical questions have been added to the exercises. Each chapter now has a summary at the end. Also, an appendix containing objective-type questions has been added. In spite of addition of a large amount of material, care has been taken to let the book remain concise and compact. All the previous figures have been redrawn. Effort has also been made to remove errors that had arisen due to misprinting in the earlier edition.

I acknowledge the efforts of the editorial and production staff of Tata McGraw-Hill Publishing Company Ltd. for bringing out the new edition in an excellent format. I am grateful to all the teachers and students who have provided several valuable suggestions for the improvement of the book.

Further comments and suggestions on the new edition are welcome.

S S RATTAN

Preface to the First Edition

Mechanisms and machines have considerable fascination for most students of mechanical engineering since the theoretical principles involved have immediate application to practical problems. The main objective of writing this book has been to present the concepts in a logical, innovative and lucid manner. The basic theory presented in the book has been evolved out of simple and readily understood principles. A sincere effort has been made to maintain physical concepts in the various derivations. The use of simple mathematical methods instead of more elegant but less obvious methods has been preferred so that those with limited mathematical skill can easily understand the exposition.

An effort has been made to give a balanced presentation of the graphical and algebraic approaches. The method chosen is that which gives a sufficiently accurate solution with the least labour. Graphical techniques have been used frequently along with the simple algebraic methods as they usually economise on effort and time. The graphical differentiation technique given in the chapter on acceleration analysis would be of considerable help to the students in their practical classes.

Computers are increasingly playing a significant role in the modern world of advanced technology. Some computer-aided problem-solving techniques have been given in the chapters on computer-aided analysis and synthesis of mechanisms.

A number of worked examples have been included to reinforce the concepts. The International System of Units (SI) has been adopted throughout the book. A bibliography at the end has been added for the convenience of students interested in additional information.

An author is always helped and influenced by many during the writing of his book. Dr N P Mehta, Dr O N Kaul and Dr B S Gill of Regional Engineering College, Kurukshetra, are only a few of many whose help I would like to acknowledge.

It is but natural that some errors creep into a work of such volume. I would appreciate if any errors and shortcomings are brought to my knowledge. Suggestions for the improvement of the book would be also welcome.

Finally, I would like to make an affectionate acknowledgement to my wife Neena, and my children Ravneet and Jasmeet, for putting up with it all so cheerfully.

S S RATTAN

Symbols and Abbreviations

(Bold face letters indicate vector quantities. The same letters in italics indicate their magnitudes)

<i>a</i>	area, addendum
ab	velocity of B relative to A
<i>A</i>	area, amplitude
<i>b</i>	width
<i>c</i>	damping coefficient
<i>C, C</i>	couple
<i>C</i>	centre distance
<i>d</i>	diameter, pitch diameter, length
<i>D</i>	diameter, operator
<i>e</i>	eccentricity, maximum fluctuation of energy, piston offset
<i>E</i>	Young's modulus, effort, energy
<i>f, f</i>	acceleration
<i>f</i>	frequency, force, stress
<i>F, F</i>	force
<i>F</i>	degree of freedom, friction
<i>g</i>	acceleration due to gravity
<i>G</i>	gear ratio, modulus of rigidity, centre of mass
<i>h</i>	length, height, lift
<i>I</i>	mass moment of inertia, instantaneous centre
<i>J</i>	polar moment of inertia
<i>k</i>	radius of gyration
<i>K</i>	coefficient of fluctuation of speed, ratio
<i>l</i>	length
<i>L</i>	length, number of loops, lead
<i>m</i>	mass, module
<i>M</i>	mass
<i>n</i>	number, ratio, speed
<i>N</i>	rotational speed (rpm), number of links
<i>p</i>	pitch, pressure, circular pitch
<i>P</i>	power, pressure, diametral pitch, planet gear, number of pairs
<i>q</i>	torsional stiffness

r, \mathbf{r}	radius
r	crank length, length
R, \mathbf{R}	reaction
R	radius
s	displacement, stiffness, length
S	slip
t	title, thickness, number of teeth
T	title period, number of teeth
T, \mathbf{T}	torque, tension
u	displacement
v, \mathbf{v}	velocity
w	width
w, \mathbf{w}	weight
x	displacement
\dot{x}	velocity (derivative of x with respect to title)
\ddot{x}	acceleration
x, y, z	cartesian coordinates
X	displacement
y	deflection, amplitude
θ	angle, angle of lap, angle between shafts
$\dot{\theta}$	angular velocity
$\ddot{\theta}$	angular acceleration
α	angle, angle of approach
α, α	angular acceleration
β	angle, angle of recess
γ	angle, pitch angle
ψ	angle, helix angle
δ	angle, angle of dwell, angle of action, increment of a quantity, logarithmic decrement
μ	coefficient of friction
ω, ω	angular velocity (rad/ s)
π	mass density
λ	angle, lead angle of worm
ε	transmissibility
ζ	damping factor
φ	angle, pressure angle, angle of friction
π	3.1416
η	efficiency
Δ	displacement
Σ	sum of quantities

Subscripts

1, 2 etc. number of degrees of freedom

a	ascent approach, addendum, axial arm
ab	A relative to B
A	annular gear
b	binary link, base circle

<i>c</i>	cam, connecting rod, centrifugal, centripetal, crossed belt, countermass, critical
<i>d</i>	descent, damped
<i>e</i>	engine
<i>f</i>	flank, friction
<i>g</i>	gear, gyroscope, gravity
<i>h</i>	horizontal
<i>i</i>	inner, input, inertia
<i>m</i>	mean
min	minimum
max	maximum
<i>n</i>	nose, normal, natural
<i>o</i>	initial value, output, outer, open belt, other links, without friction
<i>p</i>	primary, pinion, piston, crankpin, pitch line
<i>P</i>	planet
<i>r</i>	roller, recess, rack, rod, radial, resultant
<i>s</i>	sleeve, spring, secondary
<i>ss</i>	steady state
<i>S</i>	sum
<i>t</i>	tensile, ternary link, tangential
<i>v</i>	vertical
<i>w</i>	wheel
<i>x</i>	<i>x</i> component
<i>y</i>	<i>y</i> component
<i>z</i>	<i>z</i> component

Superscripts

<i>c</i>	centripetal
<i>l</i>	leading
<i>t</i>	trailing, tangential, total
<i>s</i>	sliding
<i>cr</i>	coriolis

Abbreviations

CF	complimentary function
IC	internal combustion
IDC	inner-dead centre
KE	kinetic energy
MF	magnification factor
MOI	moment of inertia
ODC	outer-dead centre
PE	potential energy
SE	strain energy
SHM	simple harmonic motion
TF	transfer function
VR	velocity ratio

Contents

Preface to the Second Edition

xvii

Preface to the First Edition

xix

Symbols and Abbreviations

xxi

1. Mechanisms and Machines

I

- 1.1 Introduction 1
- 1.2 Mechanism and Machine 2
- 1.3 Rigid and Resistant Bodies 3
- 1.4 Link 3
- 1.5 Kinematic Pair 3
- 1.6 Degrees of Freedom 6
- 1.7 Classification of Kinematic Pairs 6
- 1.8 Kinematic Chain 7
- 1.9 Linkage, Mechanism and Structure 7
- 1.10 Mobility of Mechanisms 8
- 1.11 Equivalent Mechanisms 14
- 1.12 The Four-Bar Chain 18
- 1.13 Mechanical Advantage 23
- 1.14 Transmission Angle 24
- 1.15 The Slider-Crank Chain 28
- 1.16 Double Slider-Crank Chain 32
- 1.17 Miscellaneous Mechanisms 35
- Summary* 38
- Exercises* 39

2. Velocity Analysis

42

- 2.1 Introduction 42
- 2.2 Absolute and Relative Motions 42
- 2.3 Vectors 43
- 2.4 Addition and Subtraction of Vectors 43
- 2.5 Motion of a Link 45
- 2.6 Four-Link Mechanism 46
- 2.7 Velocity Images 47
- 2.8 Angular Velocity of Links 48
- 2.9 Velocity of Rubbing 48
- 2.10 Slider-Crank Mechanism 49

- 2.11 Crank and Slotted Lever Mechanism 60
- 2.12 Algebraic Methods 68
- 2.13 Instantaneous Centre (I-Centre) 70
- 2.14 Kennedy's Theorem 71
- 2.15 Locating I-Centres 72
- 2.16 Angular Velocity Ratio Theorem 74
- 2.17 Centrode 82
 - Summary* 85
 - Exercises* 86

3. Acceleration Analysis

89

- 3.1 Introduction 89
- 3.2 Acceleration 89
- 3.3 Four-Link Mechanism 91
- 3.4 Acceleration of Intermediate and Offset Points 94
- 3.5 Slider-Crank Mechanism 95
- 3.6 Coriolis Acceleration Component 108
- 3.7 Crank and Slotted Lever Mechanism 111
- 3.8 Algebraic Methods 125
- 3.9 Klein's Construction 127
- 3.10 Velocity and Acceleration from Displacement-Time Curve 128
 - Summary* 130
 - Exercises* 130

4. Computer-aided Analysis of Mechanisms

133

- 4.1 Introduction 133
- 4.2 Four-Link Mechanism 133
- 4.3 Use of Complex Algebra 140
- 4.4 The Vector Method 141
- 4.5 Slider-Crank Mechanism 144
- 4.6 Coupler Curves 148
 - Summary* 151
 - Exercises* 153

5. Graphical and Computer-aided Synthesis of Mechanisms

154

- 5.1 Introduction 154
 - Part A: Graphical Methods 154
- 5.2 Pole 154
- 5.3 Design of Mechanisms by Relative Pole Method 158
- 5.4 Inversion Method 160
- 5.5 Design of Mechanisms by Inversion Method 161
 - Part B: Computer-Aided Synthesis of Mechanisms 164
- 5.6 To Coordinate Angular Displacement of Input and Output Links (Function Generation) 164
- 5.7 To Coordinate Angular Displacement of Input Link and Positions of a Coupler Point (Path Generation) 173

- 5.8 Rigid Body (Coupler) Guidance 180
 - Summary* 185
 - Exercises* 185

6. Lower Pairs

187

- 6.1 Introduction 187
- 6.2 Pantograph 187
- 6.3 Straight Line Mechanisms 189
- 6.4 Engine Indicators 199
- 6.5 Automobile Steering Gears 203
- 6.6 Types of Steering Gears 204
- 6.7 Hooke's Joint 208
- 6.8 Double Hooke's Joint 216
 - Summary* 218
 - Exercises* 218

7. CAMS

222

- 7.1 Introduction 222
- 7.2 Types of Cams 222
- 7.3 Types of Followers 227
- 7.4 Definitions 228
- 7.5 Follower Displacement Programming 229
- 7.6 Derivatives of Follower Motion 230
- 7.7 High Speed Cams 231
- 7.8 Undercutting 232
- 7.9 Motions of the Follower 232
- 7.10 Layout of Cam Profiles 240
- 7.11 Cams with Specified Contours 253
- 7.12 Analysis of a Rigid Eccentric Cam 265
- 7.13 Analysis of an Elastic Cam System 269
- 7.14 Spring Surge, Unbalance and Windup 272
 - Summary* 272
 - Exercises* 273

8. Friction

276

- 8.1 Introduction 276
- 8.2 Kinds of Friction 276
- 8.3 Laws of Friction 277
- 8.4 Coefficient of Friction 277
- 8.5 Inclined Plane 278
- 8.6 Screw Threads 283
- 8.7 Wedge 290
- 8.8 Pivots and Collars 294
- 8.9 Friction Clutches 300
- 8.10 Rolling Friction 314
- 8.11 Anti-Friction Bearings 315

- 8.12 Greasy Friction 316
- 8.13 Greasy Friction at a Journal 316
- 8.14 Friction Axis of a Link 317
- 8.15 Film Friction 322
- 8.16 Mitchell Thrust Bearing 324
 - Summary* 325
 - Exercises* 327

9. Belts, Ropes and Chains

330

- 9.1 Introduction 330
- 9.2 Belt and Rope Drives 331
- 9.3 Open- and Crossed-Belt Drives 332
- 9.4 Action of Belt on Pulleys 333
- 9.5 Velocity Ratio 334
- 9.6 Slip 334
- 9.7 Material for Belts and Ropes 336
- 9.8 Crowding of Pulleys 336
- 9.9 Types of Pulleys 337
- 9.10 Law of Belting 339
- 9.11 Length of Belt 340
- 9.12 Cone (Stepped) Pulleys 343
- 9.13 Ratio of Friction Tensions 346
- 9.14 Power Transmitted 349
- 9.15 Centrifugal Effect on Belts 350
- 9.16 Maximum Power Transmitted by a Belt 352
- 9.17 Initial Tension 354
- 9.18 Creep 358
- 9.19 Chains 360
- 9.20 Chain Length 361
- 9.21 Angular Speed Ratio 361
- 9.22 Classification of Chains 363
 - Summary* 365
 - Exercises* 366

10. Gears

369

- 10.1 Introduction 369
- 10.2 Classification of Gears 370
- 10.3 Gear Terminology 376
- 10.4 Law of Gearing 381
- 10.5 Velocity of Sliding 383
- 10.6 Forms of Teeth 383
- 10.7 Cycloidal Profile Teeth 384
- 10.8 Involute Profile Teeth 387
- 10.9 Interchangeable Gears 389
- 10.10 Nonstandard Gears 390
- 10.11 Path of Contact 391

10.12	Arc of Contact	392
10.13	Number of Pairs of Teeth in Contact	394
10.14	Interference in Involute Gears	397
10.15	Minimum Number of Teeth	398
10.16	Interference Between Rack and Pinion	400
10.17	Undercutting	404
10.18	Comparison of Cycloidal and Involute Tooth Forms	405
10.19	Helical and Spiral Gears	406
10.20	Terminology of Helical Gears	408
10.21	Velocity Ratio and Centre Distance of Helical Gears	409
10.22	Helical Gear Forces and Efficiency	409
10.23	Worm and Worm Gear	415
10.24	Terminology of Worm Gears	415
10.25	Velocity Ratio and Centre Distance of Worm Gears	416
10.26	Efficiency of Worm Gears	417
10.27	Bevel Gears	418
	<i>Summary</i>	420
	<i>Exercises</i>	421

11. Gear Trains

425

11.1	Introduction	425
11.2	Simple Gear Train	425
11.3	Compound Gear Train	426
11.4	Reverted Gear Train	427
11.5	Planetary or Epicycle Gear Train	427
11.6	Analysis of Epicyclic Gear Train	429
11.7	Torques in Epicyclic Trains	434
11.8	Sun And Planet Gear	440
11.9	Bevel Epicyclic Gear	444
11.10	Compound Epicyclic Gear	446
11.11	Automotive Transmission Gear Trains	447
11.12	Differentials	452
	<i>Summary</i>	454
	<i>Exercises</i>	455

12. Static Force Analysis

458

12.1	Introduction	458
12.2	Constraint and Applied Forces	458
12.3	Static Equilibrium	459
12.4	Equilibrium of Two- and Three-Force Members	459
12.5	Member with Two Forces and a Torque	460
12.6	Equilibrium of Four-Force Members	460
12.7	Force Convention	463
12.8	Free Body Diagrams	463
12.9	Superposition	464
12.10	Principle of Virtual Work	479

12.11 Friction in Mechanisms 481

Summary 487*Exercises* 487**13. Dynamic Force Analysis****490**

13.1 Introduction 490

13.2 D'Alembert's Principle 490

13.3 Equivalent Offset Inertia Force 491

13.4 Dynamic Analysis of Four-Link Mechanism 491

13.5 Dynamic Analysis of Slider-Crank Mechanism 494

13.6 Velocity and Acceleration of Piston 494

13.7 Angular Velocity and Angular Acceleration
of Connecting Rod 496

13.8 Engine Force Analysis 497

13.8 Turning Moment on Crankshaft 499

13.9 Dynamically Equivalent System 504

13.10 Inertia of the Connecting Rod 505

13.11 Inertia Force in Reciprocating Engines
(Graphical Method) 508

13.12 Turning-Moment Diagrams 522

13.13 Fluctuation of Energy 525

13.14 Flywheels 526

Summary 538*Exercises* 539**14. Balancing****542**

14.1 Introduction 542

14.2 Static Balancing 543

14.3 Dynamic Balancing 546

14.4 Transference of a Force From One Plane to Another 546

14.5 Balancing of Several Masses in Different Planes 547

14.6 Force Balancing of Linkages 554

14.7 Balancing of Reciprocating Mass 557

14.8 Balancing of Locomotives 560

14.9 Effects of Partial Balancing in Locomotives 560

14.10 Secondary Balancing 566

14.11 Balancing of Inline Engines 567

14.12 Balancing of V-Engines 585

14.13 Balancing of W, V-8 and V-12 Engines 590

14.14 Balancing of Radial Engines 592

14.15 Balancing Machines 600

14.16 Field Balancing 605

Summary 608*Exercises* 609