

OXFORD  
HIGHER EDUCATION

# ENGINEERING METROLOGY AND MEASUREMENTS

N. V. Raghavendra • L. Krishnamurthy



# ENGINEERING METROLOGY AND MEASUREMENTS

**N.V. RAGHAVENDRA**

*Professor & Head*

*Department of Mechanical Engineering*

*The National Institute of Engineering*

*Mysore*

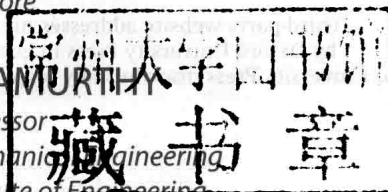
**L. KRISHNAMURTHY**

*Professor*

*Department of Mechanical Engineering*

*The National Institute of Engineering*

*Mysore*



**OXFORD**  
UNIVERSITY PRESS

# OXFORD

UNIVERSITY PRESS

Oxford University Press is a department of the University of Oxford. It furthers the University's objective of excellence in research, scholarship, and education by publishing worldwide. Oxford is a registered trade mark of Oxford University Press in the UK and in certain other countries.

Published in India by  
Oxford University Press  
YMCA Library Building, 1 Jai Singh Road, New Delhi 110001, India

© Oxford University Press 2013

The moral rights of the author/s have been asserted.

First published in 2013

All rights reserved. No part of this publication may be reproduced, stored in a retrieval system, or transmitted, in any form or by any means, without the prior permission in writing of Oxford University Press, or as expressly permitted by law, by licence, or under terms agreed with the appropriate reprographics rights organization. Enquiries concerning reproduction outside the scope of the above should be sent to the Rights Department, Oxford University Press, at the address above.

You must not circulate this work in any other form  
and you must impose this same condition on any acquirer.

ISBN-13: 978-0-19-808549-2

ISBN-10: 0-19-808549-4

Typeset in Times  
by Trinity Designers & Typesetters, Chennai  
Printed in India by Yash Printographics, Noida 201301

Third-party website addresses mentioned in this book are provided  
by Oxford University Press in good faith and for information only.  
Oxford University Press disclaims any responsibility for the material contained therein.

*Dedicated to our revered guru and mentor,  
Dr T.R. Seetharam*



# Preface

The origin of metrology can be traced to the Industrial Revolution, which began in Western Europe and the United States in the beginning of the 19th century. This period saw a transition from manual to mechanized production and the setting up of factories to manufacture iron and textiles. There was a paradigm shift from artisan-oriented production methods to mass production. An artisan produced an article the same way a storage shelf is built in a closet—by trial and error till the parts fit. Mass production called for division of labour and precise definition of production tasks. Tasks became specialized, requiring skilled people who worked on only a portion of the job, but completed it quickly and efficiently. The workers' wages were determined by a 'piece-rate' system. They were only paid for the good parts; thus it became necessary to define what a good part was. This led to the design of inspection gauges and the need for an inspector who could decide whether a part was good or not. In 1913, Henry Ford, an American industrialist, perfected the assembly line system to produce cars. In order to ensure quality as well as high production rates, new methods of inspection and quality control were initiated, which perhaps formed the basis of modern metrology.

Engineering metrology deals with the applications of measurement science in manufacturing processes. It provides a means of assessing the suitability of measuring instruments, their calibration, and the quality control of manufactured components. A product that is not manufactured according to metrological specifications will have to incur heavy costs to comply with the specifications later. Any compromise in quality creates rapid negative sentiments in the market and the cost of recovering the original market position would be quite high. Today, metrological error has a far greater impact on cost than in the past. Hence, an organization should strive towards a *zero-defect* regime in order to survive in a highly competitive market. Ensuring this aspect of manufacturing is the responsibility of a quality control engineer, who must be completely familiar with the basics of measurement, standards and systems of measurement, tolerances, measuring instruments, and their limitations.

The science of mechanical measurements has its roots in physics. It is an independent domain of knowledge dealing with the measurement of various physical quantities such as pressure, temperature, force, and flow.

## ABOUT THE BOOK

*Engineering Metrology and Measurements* is a core subject for mechanical, production, and allied disciplines in all the major universities in India. Although there are a few good books available on metrology, the coverage of topics on mechanical measurements is either scanty or superficial, necessitating students to refer to different books on mechanical measurements. This book provides a comprehensive coverage of both metrology and mechanical measurements.

Divided into three parts, the first part of the book comprising Chapters 1–11, begins with a comprehensive outline of the field of engineering metrology and its importance in mechanical engineering design and manufacturing. The basic concepts of engineering standards, limits, fits, and tolerances, for ensuring interchangeability of machine components are then discussed.

This is followed by a discussion on metrology of linear and angular measurements. Later in the book, comparators, followed by the metrology of gears, screw threads, and surface finish metrology are discussed. The chapter on miscellaneous metrology talks about laser-based instrumentation and coordinate measuring machines. The last chapter in this section features inspection methods and quality control.

The second part of the book comprising Chapters 12–16 focuses on mechanical measurements. The coverage is restricted to measurement techniques and systems that are complementary to engineering metrology. The topics covered are the basics of transducers and the measurement of force, torque, strain, temperature, and pressure.

The third part of the book comprising Chapter 17 details nanometrology techniques and instrumentation. Nanotechnology has opened a new world of scientific research and applications. India has also joined the bandwagon and today, we see a phenomenal investment in the research and development of this discipline, both in the government and private sectors. There is abundant scope for pursuing higher studies both in India and abroad. We hope this section on nanometrology will further stimulate the curiosity of the students and motivate them to take up higher studies in this new and interesting field.

The book is designed to meet the needs of undergraduate students of mechanical engineering and allied disciplines. The contents of this book have been chosen after careful perusal of the syllabi of the undergraduate (B.E./B.Tech) and diploma programmes in India. The topics are explained lucidly and are supported by self-explanatory illustrations and sketches. The following are a few key features of the book.

## KEY FEATURES

- Covers both metrology and mechanical measurements in one volume
- Offers guidelines for the proper use and maintenance of important instruments, such as vernier callipers, autocollimators, slip gauges, and pyrometers
- Provides simple solved examples, numerical exercises in all relevant chapters, theoretical review questions, and multiple-choice questions with answers at the end of every chapter
- Introduces the principles of nanometrology, a topic that has emerged from the popular discipline of nanotechnology, in an exclusive chapter, highlighting its applications in the production processes
- Includes an appendix containing 20 laboratory experiments with comprehensive procedures, observation templates, and model characteristics, with select experiments presenting photographs of the actual instruments to gain a visual understanding of the equipment used

## ONLINE RESOURCES

To aid the faculty and students using this book, the companion website of this book <http://oupinheonline.com/book/raghavendra-engineering-metrology-measurements/9780198085492> provides the following resources:

### *For instructors*

- A solutions manual for the numerical exercises given in the book

- A complete chapter-wise PowerPoint presentation to aid classroom teaching

*For students*

- Two sets of model question papers to test students' understanding of the subject, thereby preparing them for the end-semester examination.

## CONTENTS AND COVERAGE

The book is divided into three parts: Engineering Metrology (Chapters 1–11), Mechanical Measurements (Chapters 12–16), and Nano Impact on Metrology (Chapter 17). A chapter-wise scheme of the book is presented here.

*Chapter 1* deals with the basic principles of engineering metrology. It gives an overview of the subject along with its importance. It also talks about general measurement, methods of measurement, errors associated with any measurement, and the types of errors.

*Chapter 2* sets the standards of measurement. These standards acts as a reference point for the dimensional measurements.

*Chapter 3* presents the limits, fits, and tolerances in design and manufacturing. An understanding of these concepts helps in the interchangeability of manufactured components.

*Chapter 4* discusses linear measurements that form one of the most important constituents of metrology. The chapter throws light on surface plates and V-blocks, over which the measurand is inspected. It discusses the scaled, vernier, and micrometer instruments in detail. The chapter ends with a detailed explanation of slip gauges.

*Chapter 5* elaborates on angular measurements. The fact that not all measurands can be measured by linear methods stresses the significance of this topic. This chapter deals with devices such as protractors, sine bars, angle gauges, spirit levels, and other optical instruments used for angular measurements.

*Chapter 6* aids in the comprehension of comparators. In several instances, a measurement may be carried out on the basis of a comparison with the existing standards of measurements. This chapter discusses the instruments that work on this common principle.

*Chapter 7* explains optical measurements and interferometry. Optical measurement provides a simple, accurate, and reliable means of carrying out inspection and measurements in the industry. This chapter gives insights into some of the important instruments and techniques that are widely used. Interferometers, which use laser as a source, are also discussed in detail.

*Chapter 8* focuses on the metrological inspection of gears and screw threads. Gears are the main elements in a transmission system. Misalignment and gear runout will result in vibrations, chatter, noise, and loss of power. Therefore, one cannot understate the importance of precise measurement and inspection techniques for gears. Similarly, the geometric aspects of screw threads are quite complex and hence, thread gauging is an integral part of a unified thread gauging system.



*Chapter 9* analyses the metrology of surface finish. Two apparently flat contacting surfaces are assumed to be in perfect contact throughout the area of contact. However, in reality, there are peaks and valleys between surface contacts. Since mechanical engineering is primarily concerned with machines and moving parts that are designed to precisely fit with each other, surface metrology has become an important topic in engineering metrology.

*Chapter 10* comprises miscellaneous metrology, which details certain measurement principles and techniques that cannot be classified under any of the aforementioned dimensional measurements. Coordinate measuring machines (CMM), machine tool test alignment, automated inspection, and machine vision form the core of this chapter.

*Chapter 11* lays emphasis on inspection and quality control. Inspection is the scientific examination of work parts to ensure adherence to dimensional accuracy, surface texture, and other related attributes. This chapter encompasses the basic functions of inspection and statistical quality control—*total quality management* (TQM) and *six sigma*—the customer-centric approaches towards achieving high quality of products, processes, and delivery.

*Chapter 12* helps in understanding mechanical measurements. Mechanical measurements are (physical) quantity measurements unlike the dimensional measurements discussed in Chapters 1–11.

*Chapter 13* explains the principle and working of transducers. Transducers are generally defined as devices that transform physical quantities in the form of input signals into corresponding electrical output signals. Since many of the measurement principles learnt in earlier chapters require a transducer to transmit the obtained signal into an electrical form, the study of transducers is inevitable.

*Chapter 14* elucidates the physical quantities of measurement: force, torque, and strain.

*Chapter 15* illustrates the concept of temperature measurements—the principles involved in temperature measurement and devices such as resistance temperature detector (RTD), thermocouple, liquid in glass thermometer, bimetallic strip thermometers, and pyrometers.

*Chapter 16* defines yet another important physical quantity, pressure. It helps us in getting acquainted with instruments such as manometers, elastic transducers, and vacuum and high pressure measurement systems.

*Chapter 17* helps us appreciate the applications of nanotechnology in metrology. It explains the basic principles of nanotechnology and its application in the manufacturing of nanoscale elements that are made to perfection.

*Appendix A* introduces the universal measuring machine.

*Appendix B* simplifies the theory of flow measurement. Although a broader subset of mechanical measurements, flow measurement is an independent field of study. Students are introduced to this field in a typical course on fluid mechanics. Here we have tried to present only the basics of flow measurement with a synopsis of measurement devices such as the orifice meter, venturi meter, pitot tube, and rotameter.

*Appendix C* comprises 20 laboratory experiments with photographs of some of the equipment used in measurement. The appendix also provides a step-by-step procedure to conduct the experiments and an observation of results.

*Appendix D* presents the control chart associated with statistical quality control. These values help understand certain problems discussed in Chapter 11.

## ACKNOWLEDGEMENTS

We attribute our efforts for completing this book to Dr T.R. Seetharam and Dr G.L. Shekar, who have inspired us and shaped our careers. Dr. Seetharam, Professor (retired) in Mechanical Engineering and former Principal, National Institute of Engineering (NIE), Mysore, is an embodiment of scholarship and simplicity. He has motivated thousands of students, who are now in noteworthy positions in organizations all over the world. He mentored us during our formative years at the NIE and instilled in us the spirit to strive for excellence. Dr G.L. Shekar, the present Principal of NIE has been a friend, philosopher, and guide. He is a bundle of unlimited energy and has initiated a large number of research and industry-related projects at the NIE. We are happy to be associated with many of these projects, which have broadened our horizon of knowledge and provided a highly stimulating work environment.

We thank our college management, colleagues, and students, who encouraged us to work on this book. Special thanks to our esteemed colleagues, Dr B.K. Sridhara, Dr T.N. Shridhar, and Dr M.V. Achutha, for their valuable suggestions and continuous encouragement. We acknowledge the contributions of our former colleagues, Mr Manil Raj and Mr N.S. Prasad, in the preparation of the laboratory experiments provided as an appendix in the book. Special thanks to Mr K. Chandrashekar, Scientist B, Centre for Nanotechnology, NIE, for sourcing a large number of e-books on nanotechnology. Ms Pooja K., Software Engineer, Delphi Automotive Systems Pvt. Ltd, Bangalore, provided useful inputs for key chapters in Part II of the book and we thank her for the same.

We are extremely grateful to our families, who graciously accepted our inability to attend to family chores during the course of writing this book, and especially for their extended warmth and encouragement. Without their support, we would not have been able to venture into writing this book.

Last, but not the least, we express our heartfelt thanks to the editorial team at the Oxford University Press, who guided us through this project.

We eagerly look forward to your feedback. You can reach us by e-mail at raghu62.nie@gmail.com and kitty\_nie@yahoo.co.in

**N.V. Raghavendra  
L. Krishnamurthy**

# Features of the Book

CHAPTER  
1Basic Principles of  
Engineering MetrologyCHAPTER  
17

Nanometrology

## Metrology and Mechanical Measurements

One of the very few textbooks that lay equal emphasis on both metrology and mechanical measurements.

### Illustrative Schematics

The figures have been drawn in such a way so as to aid in the quick understanding of the concepts described in the ensuing text.

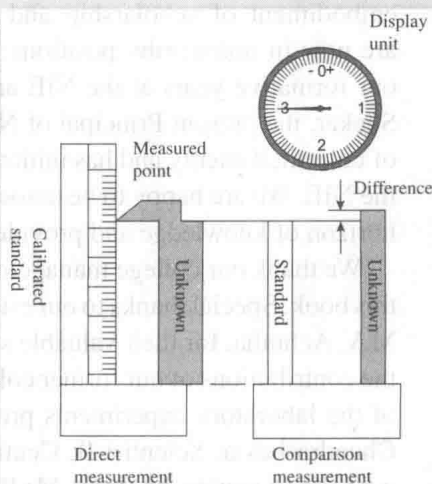


Fig. 6.1 Direct measurement versus comparison measurement

**Example 2.2** A calibrated metre end bar, which is used in the calibration of two bars X and Y, each with the metre bar, the sum of  $L_X$  and  $L_Y$  are compared, it is observed that X is 0.00 mm longer than Y.

#### A QUICK OVERVIEW

- Mass production, an idea of the last industrial revolution, has become very popular and widespread in modern manufacturing.

#### MULTIPLE-CHOICE QUESTIONS

- The modern metre is
  - (a) the length of the path travelled by light in vacuum during a time interval of  $1/29,979,245,8$  s.

#### REVIEW QUESTIONS

- Explain the role of standards of measurements in modern industry.

#### PROBLEMS

- It is required to calibrate four length bars A, B, C, and D, each having a nominal length of 100 mm.

#### Answers to Multiple-choice Questions

- |        |         |         |         |         |
|--------|---------|---------|---------|---------|
| 1. (a) | 2. (b)  | 3. (d)  | 4. (c)  | 5. (d)  |
| 9. (d) | 10. (a) | 11. (c) | 12. (b) | 13. (a) |

## Pedagogy

Provides numerical examples, exercises, end-chapter review questions, and multiple-choice questions with answers.

## Instrument Guidelines

Provides step-by-step guidelines for the use and maintenance of select instruments.

A bevel protractor is a precision angle-measuring instrument. measurement, one should follow these guidelines:

1. The instrument should be thoroughly cleaned before use. It is not recommended to use compressed air for cleaning, as it can drive particles into the instrument.
2. It is important to understand that the universal bevel protractor does not measure the angle on the work part. It measures the angle between its own base plate and the adjustable blade. Therefore, one should ensure intimate contact between the protractor and the features of the part.
3. An easy method to determine if the blade is in contact with the work part is to look behind it and adjust the blade so that no light leaks between the two.
4. It should always be ensured that the instrument is in a plane parallel to the surface being measured. In the absence of this condition, the angle measured will be erroneous.
5. The accuracy of measurement also depends on the surface quality.

## CHAPTER 17

## Nanometrology

After studying this chapter, the reader will be able to

- acquire basic understanding of the field of nanotechnology

## Chapter on Nanometrology

With the field of nanotechnology having an impact on almost every discipline of science and technology, this is the only Indian textbook to discuss this topic.

## Laboratory Experiments

Appendix C contains 20 experiments usually demonstrated in a typical laboratory course on the subject. Select experiments also feature photographs of the devices used for experimentation. It contains procedures, observation templates, and model characteristics of all relevant experiments.

### C.4 STUDY OF BEVEL PROTRACTORS

#### C.4.1 Aim

To determine the angle of a given specimen

#### C.4.2 Apparatus

The following items are used for measurement:

1. Bevel protractor
2. Specimen

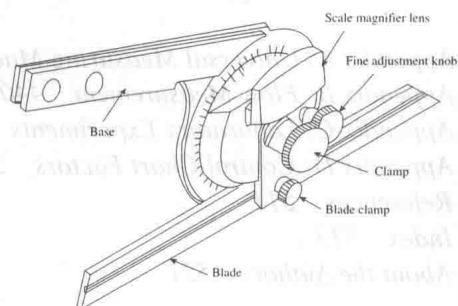


Fig. C.9 Bevel protractor

#### C.4.3 Theory

A bevel protractor, as shown in Fig. C.9, is used for measuring angles and laying out angles within an accuracy of 5'. The protractor dial is slotted to hold a blade, which can be

# Brief Contents

<i>Preface</i>	v
<i>Features of the Book</i>	x
<i>Detailed Contents</i>	xiii

## **PART I: ENGINEERING METROLOGY 1**

1. Basic Principles of Engineering Metrology	3
2. Standards of Measurement	20
3. Limits, Fits, and Tolerances	39
4. Linear Measurement	80
5. Angular Measurement	118
6. Comparators	141
7. Optical Measurement and Interferometry	167
8. Metrology of Gears and Screw Threads	188
9. Metrology of Surface Finish	217
10. Miscellaneous Metrology	231
11. Inspection and Quality Control	260

## **PART II: MECHANICAL MEASUREMENTS 303**

12. Measurement Systems	305
13. Transducers	315
14. Measurement of Force, Torque, and Strain	341
15. Measurement of Temperature	365
16. Pressure Measurements	387

## **PART III: NANO IMPACT ON METROLOGY 411**

17. Nanometrology	413
-------------------	-----

<i>Appendix A: Universal Measuring Machine</i>	439
<i>Appendix B: Flow Measurement</i>	440
<i>Appendix C: Laboratory Experiments</i>	445
<i>Appendix D: Control Chart Factors</i>	509
<i>References</i>	511
<i>Index</i>	513
<i>About the Authors</i>	521



# Detailed Contents

*Preface* v

*Features of the Book* x

*Brief Contents* xii

## PART I: ENGINEERING METROLOGY

1

### 1. Basic Principles of Engineering

#### Metrology 3

1.1 Introduction 3

1.2 Metrology 4

1.3 Need for Inspection 5

1.4 Accuracy and Precision 7

1.4.1 Accuracy and Cost 9

1.5 Objectives of Metrology and Measurements 9

1.6 General Measurement Concepts 10

1.6.1 Calibration of Measuring Instruments 10

1.7 Errors in Measurements 11

1.7.1 Systematic or Controllable Errors 12

1.7.2 Random Errors 14

1.8 Methods of Measurement 15

### 2. Standards of Measurement 20

2.1 Introduction 20

2.2 Standards and their Roles 20

2.3 Evolution of Standards 21

2.4 National Physical Laboratory 23

2.5 Material Standard 23

2.5.1 Yard 24

2.5.2 Metre 25

2.5.3 Disadvantages of Material Standards 25

2.6 Wavelength Standard 25

2.6.1 Modern Metre 26

2.7 Subdivisions of Standards 26

2.8 Line and End Measurements 28

2.8.1 Characteristics of Line Standards 28

2.8.2 Characteristics of End Standards 29

2.8.3 Transfer from Line Standard to End Standard 30

2.9 Brookes Level Comparator 31

2.10 Displacement Method 32

2.11 Calibration of End Bars 33

2.12 Numerical Examples 33

### 3. Limits, Fits, and Tolerances 39

3.1 Introduction 39

3.2 Principle of Interchangeability 41

3.2.1 Selective Assembly Approach 42

3.3 Tolerances 43

3.3.1 Computer-aided Modelling 43

3.3.2 Manufacturing Cost and Work Tolerance 44

3.3.3 Classification of Tolerance 44

3.4 Maximum and Minimum Metal Conditions 48

3.5 Fits 48

3.5.1 Allowance 50

3.5.2 Hole Basis and Shaft Basis Systems 51

3.5.3 Numerical Examples 52

3.6 System of Limits and Fits 56

3.6.1 General Terminology 61

3.6.2 Limit Gauging 63

3.6.3 Classification of Gauges 65

3.6.4 Taylor's Principle 66

3.6.5 Important Points for Gauge Design 67

3.6.6 Material for Gauges 68

3.6.7 Gauge Tolerance (Gauge Maker's Tolerance) 68

3.6.8 Wear Allowance 69

3.6.9 Methods of Tolerance Specification on Gauges 69

3.6.10 Numerical Examples	71	5.3.3 Sine Blocks, Sine Plates, and Sine Tables	125
3.7 Plain Plug Gauges	74	5.3.4 Sine Centre	126
3.8 Snap Gauges	75	5.4 Angle Gauges	126
<b>4. Linear Measurement</b>	<b>80</b>	5.4.1 Uses	128
4.1 Introduction	80	5.4.2 Manufacture and Calibration	129
4.2 Design of Linear Measurement Instruments	81	5.4.3 True Square	130
4.3 Surface Plate	82	5.5 Spirit Level	130
4.4 V-blocks	85	5.5.1 Clinometer	132
4.5 Graduated Scales	85	5.6 Optical Instruments for Angular Measurement	132
4.5.1 Errors in Measurements	86	5.6.1 Autocollimator	133
4.6 Scaled Instruments	88	5.6.2 Autocollimator Applications	135
4.6.1 Depth Gauge	88	5.6.3 Angle Dekkor	137
4.6.2 Combination Set	89	<b>6. Comparators</b>	<b>141</b>
4.6.3 Callipers	91	6.1 Introduction	141
4.7 Vernier Instruments	94	6.2 Functional Requirements	142
4.7.1 Vernier Calliper	95	6.3 Classification of Comparators	143
4.7.2 Vernier Depth Gauge	98	6.4 Mechanical Comparators	143
4.7.3 Vernier Height Gauge	99	6.4.1 Dial Indicator	143
4.8 Micrometer Instruments	99	6.4.2 Johansson Mikrokator	147
4.8.1 Outside Micrometer	100	6.4.3 Sigma Comparator	148
4.8.2 Vernier Micrometer	103	6.5 Mechanical-Optical Comparator	148
4.8.3 Digital Micrometer	104	6.5.1 Zeiss Ultra-optimeter	149
4.8.4 Inside Micrometer Calliper	105	6.5.2 Optical Projector	150
4.8.5 Inside Micrometer	105	6.6 Electrical Comparators	151
4.8.6 Depth Micrometer	106	6.6.1 Linear Variable Differential Transformer	152
4.8.7 Floating Carriage Micrometer	107	6.6.2 Electronic Comparator	153
4.9 Slip Gauges	107	6.7 Pneumatic Comparators	156
4.9.1 Gauge Block Shapes, Grades, and Sizes	109	6.7.1 Free Flow Air Gauge	157
4.9.2 Wringing of Slip Gauges	110	6.7.2 Back Pressure Gauge	159
4.9.3 Manufacture of Slip Gauges	112	6.7.3 Solex Pneumatic Gauge	161
4.9.4 Calibration of Slip Gauges	112	6.7.4 Applications of Pneumatic Comparators	162
4.10 Numerical Examples	113	<b>7. Optical Measurement and Interferometry</b>	<b>167</b>
<b>5. Angular Measurement</b>	<b>118</b>	7.1 Introduction	167
5.1 Introduction	118	7.2 Optical Measurement Techniques	168
5.2 Protractor	119	7.2.1 Tool Maker's Microscope	168
5.2.1 Universal Bevel Protractor	119	7.2.2 Profile Projector	171
5.2.2 Optical Bevel Protractor	122	7.2.3 Optical Squares	171
5.3 Sine Bar	123	7.3 Optical Interference	172
5.3.1 Setting the Sine Bars to Desired Angles	124	7.4 Interferometry	174
5.3.2 Measuring Unknown Angles with Sine Bar	125	7.4.1 Optical Flats	174

7.5 Interferometers	177	9.3 Terminology	219
7.5.1 NPL Flatness Interferometer	177	9.4 Analysis of Surface Traces	220
7.5.2 Pitter–NPL Gauge Interferometer	179	9.4.1 Ten-point Height Average Value	220
7.5.3 Laser Interferometers	180	9.4.2 Root Mean Square Value	220
7.6 Scales, Gratings, and Reticles	181	9.4.3 Centre Line Average Value	220
7.6.1 Scales	182	9.5 Specification of Surface Texture Characteristics	221
7.6.2 Gratings	182	9.6 Methods of Measuring Surface Finish	222
7.6.3 Reticles	182	9.7 Stylus System of Measurement	223
7.7 Numerical Examples	183	9.7.1 Stylus and Datum	223
<b>8. Metrology of Gears and Screw Threads</b>	<b>188</b>	9.8 Stylus Probe Instruments	224
8.1 Introduction	188	9.8.1 Tomlinson Surface Meter	224
8.2 Gear Terminology	189	9.8.2 Taylor–Hobson Talysurf	225
8.2.1 Types of Gears	189	9.8.3 Profilometer	225
8.2.2 Line of Action and Pressure Angle	192	9.9 Wavelength, Frequency, and Cut-off	226
8.3 Errors in Spur Gears	192	9.9.1 Cut-off Wavelength	226
8.4 Measurement of Gear Elements	193	9.10 Other Methods for Measuring Surface Roughness	227
8.4.1 Measurement of Runout	193	9.10.1 Pneumatic Method	227
8.4.2 Measurement of Pitch	194	9.10.2 Light Interference Microscopes	227
8.4.3 Measurement of Profile	195	9.10.3 Mecnin Instrument	227
8.4.4 Measurement of Lead	197	<b>10. Miscellaneous Metrology</b>	<b>231</b>
8.4.5 Measurement of Backlash	197	10.1 Introduction	231
8.4.6 Measurement of Tooth Thickness	198	10.2 Precision Instrumentation Based on Laser Principles	232
8.5 Composite Method of Gear Inspection	201	10.3 Coordinate Measuring Machines	233
8.5.1 Parkinson Gear Tester	201	10.3.1 Structure	234
8.6 Measurement of Screw Threads	202	10.3.2 Modes of Operation	235
8.7 Screw Thread Terminology	203	10.3.3 Probe	235
8.8 Measurement of Screw Thread Elements	204	10.3.4 Operation	236
8.8.1 Measurement of Major Diameter	205	10.3.5 Major Applications	238
8.8.2 Measurement of Minor Diameter	205	10.4 Machine Tool Metrology	238
8.8.3 Measurement of Effective Diameter	206	10.4.1 Straightness, Flatness, Parallelism, Squareness, Roundness, Cylindricity, and Runout	239
8.8.4 Measurement of Pitch	209	10.4.2 Acceptance Tests for Machine Tools	244
8.9 Thread Gauges	210	10.5 Automated Inspection	251
8.10 Numerical Examples	212	10.5.1 Flexible Inspection System	253
<b>9. Metrology of Surface Finish</b>	<b>217</b>	10.6 Machine Vision	253
9.1 Introduction	217	10.6.1 Stages of Machine Vision	253
9.2 Surface Metrology Concepts	218		



10.6.2 Applications of Machine Vision in Inspection	256	11.9 Total Quality Management	278
<b>11. Inspection and Quality Control</b>	<b>260</b>	11.9.1 Customer Focus	279
11.1 Introduction	260	11.9.2 Continuous Improvement	280
11.2 Inspection	261	11.9.3 Employee Empowerment	280
11.3 Specifying Limits of Variability	262	11.9.4 Use of Quality Tools	281
11.4 Dimensions and Tolerances	264	11.9.5 Product Design	282
11.5 Selection of Gauging Equipment	265	11.9.6 Process Management	282
11.6 Gauge Control	266	11.9.7 Managing Supplier Quality	283
11.7 Quality Control and Quality Assurance	267	11.10 Six Sigma	284
11.8 Statistical Quality Control	269	11.10.1 Six Sigma Approach	285
11.8.1 Process Variability	269	11.10.2 Training for Six Sigma	286
11.8.2 Importance of Sampling	270	11.11 Quality Standards	286
11.8.3 Statistical Quality Control by Attributes	272	11.11.1 Quality Management Principles of ISO 9000	287
11.8.4 Statistical Quality Control by Variables	273	11.11.2 Implementation of ISO Standards	289
		11.12 Numerical Examples	289
		<i>Annexure I—Control Chart Factors</i>	301

## PART II: MECHANICAL MEASUREMENTS

303

<b>12. Measurement Systems</b>	<b>305</b>	13.3.1 Primary and Secondary Transducers	316
12.1 Introduction	305	13.3.2 Based on Principle of Transduction	317
12.2 Some Basic Definitions	305	13.3.3 Active and Passive Transducers	318
12.2.1 Hysteresis in Measurement Systems	306	13.3.4 Analog and Digital Transducers	318
12.2.2 Linearity in Measurement Systems	306	13.3.5 Direct and Inverse Transducers	318
12.2.3 Resolution of Measuring Instruments	307	13.3.6 Null- and Deflection-type Transducers	319
12.2.4 Threshold	308	13.4 Quality Attributes for Transducers	320
12.2.5 Drift	308	13.5 Intermediate Modifying Devices	320
12.2.6 Zero Stability	308	13.5.1 Inherent Problems in Mechanical Systems	321
12.2.7 Loading Effects	308	13.5.2 Kinematic Linearity	322
12.2.8 System Response	308	13.5.3 Mechanical Amplification	322
12.3 Functional Elements of Measurement Systems	309	13.5.3 Reflected Frictional Amplification	322
12.4 Primary Detector-Transducer Stage	310	13.5.4 Reflected Inertial Amplification	323
12.5 Intermediate Modifying Stage	311	13.5.5 Amplification of Backlash and Elastic Deformation	323
12.6 Output or Terminating Stage	312		
<b>13. Transducers</b>	<b>315</b>		
13.1 Introduction	315		
13.2 Transfer Efficiency	315		
13.3 Classification of Transducers	316		