

- Preface p. xvii
- Acknowledgements p. xx
- Part 1 Principles of Measurement p. 1
- 1 Introduction to Measurement p. 3
- 1.1 Measurement units p. 3
- 1.2 Measurement system applications p. 6
- 1.3 Elements of a measurement system p. 8
- 1.4 Choosing appropriate measuring instruments p. 9
- 2 Instrument Types and Performance Characteristics p. 12
- 2.1 Review of instrument types p. 12
- 2.1.1 Active and passive instruments p. 12
- 2.1.2 Null-type and deflection-type instruments p. 13
- 2.1.3 Analogue and digital instruments p. 14
- 2.1.4 Indicating instruments and instruments with a signal output p. 15
- 2.1.5 Smart and non-smart instruments p. 16
- 2.2 Static characteristics of instruments p. 16
- 2.2.1 Accuracy and inaccuracy (measurement uncertainty) p. 16
- 2.2.2 Precision/repeatability/reproducibility p. 17
- 2.2.3 Tolerance p. 17
- 2.2.4 Range or span p. 18
- 2.2.5 Linearity p. 19
- 2.2.6 Sensitivity of measurement p. 19
- 2.2.7 Threshold p. 20
- 2.2.8 Resolution p. 20
- 2.2.9 Sensitivity to disturbance p. 20
- 2.2.10 Hysteresis effects p. 22
- 2.2.11 Dead space p. 23
- 2.3 Dynamic characteristics of instruments p. 23
- 2.3.1 Zero order instrument p. 25
- 2.3.2 First order instrument p. 25
- 2.3.3 Second order instrument p. 28
- 2.4 Necessity for calibration p. 29
- 2.5 Self-test questions p. 30
- 3 Errors During the Measurement Process p. 32
- 3.1 Introduction p. 32
- 3.2 Sources of systematic error p. 33
- 3.2.1 System disturbance due to measurement p. 33
- 3.2.2 Errors due to environmental inputs p. 37
- 3.2.3 Wear in instrument components p. 38
- 3.2.4 Connecting leads p. 38
- 3.3 Reduction of systematic errors p. 39
- 3.3.1 Careful instrument design p. 39
- 3.3.2 Method of opposing inputs p. 39
- 3.3.3 High-gain feedback p. 39
- 3.3.4 Calibration p. 41
- 3.3.5 Manual correction of output reading p. 42

- 3.3.6 Intelligent instruments p. 42
- 3.4 Quantification of systematic errors p. 42
- 3.5 Random errors p. 42
- 3.5.1 Statistical analysis of measurements subject to random errors p. 43
- 3.5.2 Graphical data analysis techniques--frequency distributions p. 46
- 3.6 Aggregation of measurement system errors p. 56
- 3.6.1 Combined effect of systematic and random errors p. 56
- 3.6.2 Aggregation of errors from separate measurement system components p. 56
- 3.6.3 Total error when combining multiple measurements p. 59
- 3.7 Self-test questions p. 60
- References and further reading p. 63
- 4 Calibration of Measuring Sensors and Instruments p. 64
- 4.1 Principles of calibration p. 64
- 4.2 Control of calibration environment p. 66
- 4.3 Calibration chain and traceability p. 67
- 4.4 Calibration records p. 71
- References and further reading p. 72
- 5 Measurement Noise and Signal Processing p. 73
- 5.1 Sources of measurement noise p. 73
- 5.1.1 Inductive coupling p. 74
- 5.1.2 Capacitive (electrostatic) coupling p. 74
- 5.1.3 Noise due to multiple earths p. 74
- 5.1.4 Noise in the form of voltage transients p. 75
- 5.1.5 Thermoelectric potentials p. 75
- 5.1.6 Shot noise p. 76
- 5.1.7 Electrochemical potentials p. 76
- 5.2 Techniques for reducing measurement noise p. 76
- 5.2.1 Location and design of signal wires p. 76
- 5.2.2 Earthing p. 77
- 5.2.3 Shielding p. 77
- 5.2.4 Other techniques p. 77
- 5.3 Introduction to signal processing p. 78
- 5.4 Analogue signal filtering p. 78
- 5.4.1 Passive analogue filters p. 81
- 5.4.2 Active analogue filters p. 85
- 5.5 Other analogue signal processing operations p. 86
- 5.5.1 Signal amplification p. 87
- 5.5.2 Signal attenuation p. 88
- 5.5.3 Differential amplification p. 89
- 5.5.4 Signal linearization p. 90
- 5.5.5 Bias (zero drift) removal p. 91
- 5.5.6 Signal integration p. 92
- 5.5.7 Voltage follower (pre-amplifier) p. 92
- 5.5.8 Voltage comparator p. 92
- 5.5.9 Phase-sensitive detector p. 93
- 5.5.10 Lock-in amplifier p. 94

- 5.5.11 Signal addition p. 94
- 5.5.12 Signal multiplication p. 95
- 5.6 Digital signal processing p. 95
- 5.6.1 Signal sampling p. 95
- 5.6.2 Sample and hold circuit p. 97
- 5.6.3 Analogue-to-digital converters p. 97
- 5.6.4 Digital-to-analogue (D/A) conversion p. 99
- 5.6.5 Digital filtering p. 100
- 5.6.6 Autocorrelation p. 100
- 5.6.7 Other digital signal processing operations p. 101
- References and further reading p. 101
- 6 Electrical Indicating and Test Instruments p. 102
- 6.1 Digital meters p. 102
- 6.1.1 Voltage-to-time conversion digital voltmeter p. 103
- 6.1.2 Potentiometric digital voltmeter p. 103
- 6.1.3 Dual-slope integration digital voltmeter p. 103
- 6.1.4 Voltage-to-frequency conversion digital voltmeter p. 104
- 6.1.5 Digital multimeter p. 104
- 6.2 Analogue meters p. 104
- 6.2.1 Moving-coil meters p. 105
- 6.2.2 Moving-iron meter p. 106
- 6.2.3 Electrodynamometric meters p. 107
- 6.2.4 Clamp-on meters p. 108
- 6.2.5 Analogue multimeter p. 108
- 6.2.6 Measuring high-frequency signals p. 109
- 6.2.7 Thermocouple meter p. 110
- 6.2.8 Electronic analogue voltmeters p. 111
- 6.2.9 Calculation of meter outputs for non-standard waveforms p. 112
- 6.3 Cathode ray oscilloscope p. 114
- 6.3.1 Cathode ray tube p. 115
- 6.3.2 Channel p. 116
- 6.3.3 Single-ended input p. 117
- 6.3.4 Differential input p. 117
- 6.3.5 Timebase circuit p. 117
- 6.3.6 Vertical sensitivity control p. 117
- 6.3.7 Display position control p. 118
- 6.4 Digital storage oscilloscopes p. 118
- References and further reading p. 118
- 7 Variable Conversion Elements p. 119
- 7.1 Bridge circuits p. 119
- 7.1.1 Null-type, d.c. bridge (Wheatstone bridge) p. 120
- 7.1.2 Deflection-type d.c. bridge p. 121
- 7.1.3 Error analysis p. 128
- 7.1.4 A.c. bridges p. 130
- 7.2 Resistance measurement p. 134
- 7.2.1 D.c. bridge circuit p. 135

- 7.2.2 Voltmeter-ammeter method p. 135
- 7.2.3 Resistance-substitution method p. 135
- 7.2.4 Use of the digital voltmeter to measure resistance p. 136
- 7.2.5 The ohmmeter p. 136
- 7.2.6 Codes for resistor values p. 137
- 7.3 Inductance measurement p. 138
- 7.4 Capacitance measurement p. 138
- 7.4.1 Alphanumeric codes for capacitor values p. 139
- 7.5 Current measurement p. 140
- 7.6 Frequency measurement p. 141
- 7.6.1 Digital counter-timers p. 142
- 7.6.2 Phase-locked loop p. 142
- 7.6.3 Cathode ray oscilloscope p. 143
- 7.6.4 The Wien bridge p. 144
- 7.7 Phase measurement p. 145
- 7.7.1 Electronic counter-timer p. 145
- 7.7.2 X-Y plotter p. 145
- 7.7.3 Oscilloscope p. 147
- 7.7.4 Phase-sensitive detector p. 147
- 7.8 Self-test questions p. 147
- References and further reading p. 150
- 8 Signal Transmission p. 151
- 8.1 Electrical transmission p. 151
- 8.1.1 Transmission as varying voltages p. 151
- 8.1.2 Current loop transmission p. 152
- 8.1.3 Transmission using an a.c. carrier p. 153
- 8.2 Pneumatic transmission p. 154
- 8.3 Fibre-optic transmission p. 155
- 8.3.1 Principles of fibre optics p. 156
- 8.3.2 Transmission characteristics p. 158
- 8.3.3 Multiplexing schemes p. 160
- 8.4 Optical wireless telemetry p. 160
- 8.5 Radio telemetry (radio wireless transmission) p. 161
- 8.6 Digital transmission protocols p. 163
- References and further reading p. 164
- 9 Digital Computation and Intelligent Devices p. 165
- 9.1 Principles of digital computation p. 165
- 9.1.1 Elements of a computer p. 165
- 9.1.2 Computer operation p. 168
- 9.1.3 Interfacing p. 174
- 9.1.4 Practical considerations in adding computers to measurement systems p. 176
- 9.2 Intelligent devices p. 177
- 9.2.1 Intelligent instruments p. 177
- 9.2.2 Smart sensors p. 179
- 9.2.3 Smart transmitters p. 180
- 9.2.4 Communication with intelligent devices p. 183

- 9.2.5 Computation in intelligent devices p. 184
- 9.2.6 Future trends in intelligent devices p. 185
- 9.3 Self-test questions p. 185
- References and further reading p. 186
- 10 Instrumentation/Computer Networks p. 187
- 10.1 Introduction p. 187
- 10.2 Serial communication lines p. 188
- 10.2.1 Asynchronous transmission p. 189
- 10.3 Parallel data bus p. 190
- 10.4 Local area networks (LANs) p. 192
- 10.4.1 Star networks p. 193
- 10.4.2 Ring and bus networks p. 194
- 10.5 Gateways p. 195
- 10.6 HART p. 195
- 10.7 Digital fieldbuses p. 196
- 10.8 Communication protocols for very large systems p. 198
- 10.8.1 Protocol standardization p. 198
- 10.9 Future development of networks p. 199
- References and further reading p. 199
- 11 Display, Recording and Presentation of Measurement Data p. 200
- 11.1 Display of measurement signals p. 200
- 11.1.1 Electronic output displays p. 200
- 11.1.2 Computer monitor displays p. 201
- 11.2 Recording of measurement data p. 202
- 11.2.1 Mechanical chart recorders p. 202
- 11.2.2 Ultra-violet recorders p. 208
- 11.2.3 Fibre-optic recorders (recording oscilloscopes) p. 209
- 11.2.4 Hybrid chart recorders p. 209
- 11.2.5 Magnetic tape recorders p. 209
- 11.2.6 Digital recorders p. 210
- 11.2.7 Storage oscilloscopes p. 211
- 11.3 Presentation of data p. 212
- 11.3.1 Tabular data presentation p. 212
- 11.3.2 Graphical presentation of data p. 213
- 11.4 Self-test questions p. 222
- References and further reading p. 223
- 12 Measurement Reliability and Safety Systems p. 224
- 12.1 Reliability p. 224
- 12.1.1 Principles of reliability p. 224
- 12.1.2 Laws of reliability in complex systems p. 228
- 12.1.3 Improving measurement system reliability p. 229
- 12.1.4 Software reliability p. 232
- 12.2 Safety systems p. 236
- 12.2.1 Introduction to safety systems p. 236
- 12.2.2 Operation of safety systems p. 237
- 12.2.3 Design of a safety system p. 238

- 12.3 Self-test questions p. 241
- References and further reading p. 242
- Part 2 Measurement Sensors and Instruments p. 245
- 13 Sensor Technologies p. 247
- 13.1 Capacitive and resistive sensors p. 247
- 13.2 Magnetic sensors p. 247
- 13.3 Hall-effect sensors p. 249
- 13.4 Piezoelectric transducers p. 250
- 13.5 Strain gauges p. 251
- 13.6 Piezoresistive sensors p. 252
- 13.7 Optical sensors (air path) p. 252
- 13.8 Optical sensors (fibre-optic) p. 253
- 13.8.1 Intrinsic sensors p. 254
- 13.8.2 Extrinsic sensors p. 258
- 13.8.3 Distributed sensors p. 259
- 13.9 Ultrasonic transducers p. 259
- 13.9.1 Transmission speed p. 260
- 13.9.2 Direction of travel of ultrasound waves p. 261
- 13.9.3 Directionality of ultrasound waves p. 261
- 13.9.4 Relationship between wavelength, frequency and directionality of ultrasound waves p. 262
- 13.9.5 Attenuation of ultrasound waves p. 262
- 13.9.6 Ultrasound as a range sensor p. 263
- 13.9.7 Use of ultrasound in tracking 3D object motion p. 264
- 13.9.8 Effect of noise in ultrasonic measurement systems p. 265
- 13.9.9 Exploiting Doppler shift in ultrasound transmission p. 265
- 13.9.10 Ultrasonic imaging p. 267
- 13.10 Nuclear sensors p. 267
- 13.11 Microsensors p. 268
- References and further reading p. 270
- 14 Temperature Measurement p. 271
- 14.1 Principles of temperature measurement p. 271
- 14.2 Thermoelectric effect sensors (thermocouples) p. 272
- 14.2.1 Thermocouple tables p. 276
- 14.2.2 Non-zero reference junction temperature p. 277
- 14.2.3 Thermocouple types p. 279
- 14.2.4 Thermocouple protection p. 280
- 14.2.5 Thermocouple manufacture p. 281
- 14.2.6 The thermopile p. 282
- 14.2.7 Digital thermometer p. 282
- 14.2.8 The continuous thermocouple p. 282
- 14.3 Varying resistance devices p. 283
- 14.3.1 Resistance thermometers (resistance temperature devices) p. 284
- 14.3.2 Thermistors p. 285
- 14.4 Semiconductor devices p. 286
- 14.5 Radiation thermometers p. 287

- 14.5.1 Optical pyrometers p. 289
- 14.5.2 Radiation pyrometers p. 290
- 14.6 Thermography (thermal imaging) p. 293
- 14.7 Thermal expansion methods p. 294
- 14.7.1 Liquid-in-glass thermometers p. 295
- 14.7.2 Bimetallic thermometer p. 296
- 14.7.3 Pressure thermometers p. 296
- 14.8 Quartz thermometers p. 297
- 14.9 Fibre-optic temperature sensors p. 297
- 14.10 Acoustic thermometers p. 298
- 14.11 Colour indicators p. 299
- 14.12 Change of state of materials p. 299
- 14.13 Intelligent temperature-measuring instruments p. 300
- 14.14 Choice between temperature transducers p. 300
- 14.15 Self-test questions p. 302
- References and further reading p. 303
- 15 Pressure Measurement p. 304
- 15.1 Diaphragms p. 305
- 15.2 Capacitive pressure sensor p. 306
- 15.3 Fibre-optic pressure sensors p. 306
- 15.4 Bellows p. 307
- 15.5 Bourdon tube p. 308
- 15.6 Manometers p. 310
- 15.7 Resonant-wire devices p. 311
- 15.8 Dead-weight gauge p. 312
- 15.9 Special measurement devices for low pressures p. 312
- 15.10 High-pressure measurement (greater than 7000 bar) p. 315
- 15.11 Intelligent pressure transducers p. 316
- 15.12 Selection of pressure sensors p. 316
- 16 Flow Measurement p. 319
- 16.1 Mass flow rate p. 319
- 16.1.1 Conveyor-based methods p. 319
- 16.1.2 Coriolis flowmeter p. 320
- 16.1.3 Thermal mass flow measurement p. 320
- 16.1.4 Joint measurement of volume flow rate and fluid density p. 321
- 16.2 Volume flow rate p. 321
- 16.2.1 Differential pressure (obstruction-type) meters p. 322
- 16.2.2 Variable area flowmeters (Rotameters) p. 327
- 16.2.3 Positive displacement flowmeters p. 328
- 16.2.4 Turbine meters p. 329
- 16.2.5 Electromagnetic flowmeters p. 330
- 16.2.6 Vortex-shedding flowmeters p. 332
- 16.2.7 Ultrasonic flowmeters p. 332
- 16.2.8 Other types of flowmeter for measuring volume flow rate p. 336
- 16.3 Intelligent flowmeters p. 338
- 16.4 Choice between flowmeters for particular applications p. 338

- References and further reading p. 339
- 17 Level Measurement p. 340
- 17.1 Dipsticks p. 340
- 17.2 Float systems p. 340
- 17.3 Pressure-measuring devices (hydrostatic systems) p. 341
- 17.4 Capacitive devices p. 343
- 17.5 Ultrasonic level gauge p. 344
- 17.6 Radar (microwave) methods p. 346
- 17.7 Radiation methods p. 346
- 17.8 Other techniques p. 348
- 17.8.1 Vibrating level sensor p. 348
- 17.8.2 Hot-wire elements/carbon resistor elements p. 348
- 17.8.3 Laser methods p. 349
- 17.8.4 Fibre-optic level sensors p. 349
- 17.8.5 Thermography p. 349
- 17.9 Intelligent level-measuring instruments p. 351
- 17.10 Choice between different level sensors p. 351
- References and further reading p. 351
- 18 Mass, Force and Torque Measurement p. 352
- 18.1 Mass (weight) measurement p. 352
- 18.1.1 Electronic load cell (electronic balance) p. 352
- 18.1.2 Pneumatic/hydraulic load cells p. 354
- 18.1.3 Intelligent load cells p. 355
- 18.1.4 Mass-balance (weighing) instruments p. 356
- 18.1.5 Spring balance p. 359
- 18.2 Force measurement p. 359
- 18.2.1 Use of accelerometers p. 360
- 18.2.2 Vibrating wire sensor p. 360
- 18.3 Torque measurement p. 361
- 18.3.1 Reaction forces in shaft bearings p. 361
- 18.3.2 Prony brake p. 361
- 18.3.3 Measurement of induced strain p. 362
- 18.3.4 Optical torque measurement p. 364
- 19 Translational Motion Transducers p. 365
- 19.1 Displacement p. 365
- 19.1.1 The resistive potentiometer p. 365
- 19.1.2 Linear variable differential transformer (LVDT) p. 368
- 19.1.3 Variable capacitance transducers p. 370
- 19.1.4 Variable inductance transducers p. 371
- 19.1.5 Strain gauges p. 371
- 19.1.6 Piezoelectric transducers p. 373
- 19.1.7 Nozzle flapper p. 373
- 19.1.8 Other methods of measuring small displacements p. 374
- 19.1.9 Measurement of large displacements (range sensors) p. 378
- 19.1.10 Proximity sensors p. 381
- 19.1.11 Selection of translational measurement transducers p. 382



- 19.2 Velocity p. 382
- 19.2.1 Differentiation of displacement measurements p. 382
- 19.2.2 Integration of the output of an accelerometer p. 383
- 19.2.3 Conversion to rotational velocity p. 383
- 19.3 Acceleration p. 383
- 19.3.1 Selection of accelerometers p. 385
- 19.4 Vibration p. 386
- 19.4.1 Nature of vibration p. 386
- 19.4.2 Vibration measurement p. 386
- 19.5 Shock p. 388
- 20 Rotational Motion Transducers p. 390
- 20.1 Rotational displacement p. 390
- 20.1.1 Circular and helical potentiometers p. 390
- 20.1.2 Rotational differential transformer p. 391
- 20.1.3 Incremental shaft encoders p. 392
- 20.1.4 Coded-disc shaft encoders p. 394
- 20.1.5 The resolver p. 398
- 20.1.6 The synchro p. 399
- 20.1.7 The induction potentiometer p. 402
- 20.1.8 The rotary inductosyn p. 402
- 20.1.9 Gyroscopes p. 402
- 20.1.10 Choice between rotational displacement transducers p. 406
- 20.2 Rotational velocity p. 407
- 20.2.1 Digital tachometers p. 407
- 20.2.2 Stroboscopic methods p. 410
- 20.2.3 Analogue tachometers p. 411
- 20.2.4 Mechanical flyball p. 413
- 20.2.5 The rate gyroscope p. 415
- 20.2.6 Fibre-optic gyroscope p. 416
- 20.2.7 Differentiation of angular displacement measurements p. 417
- 20.2.8 Integration of the output from an accelerometer p. 417
- 20.2.9 Choice between rotational velocity transducers p. 417
- 20.3 Measurement of rotational acceleration p. 417
- References and further reading p. 418
- 21 Summary of Other Measurements p. 419
- 21.1 Dimension measurement p. 419
- 21.1.1 Rules and tapes p. 419
- 21.1.2 Callipers p. 421
- 21.1.3 Micrometers p. 422
- 21.1.4 Gauge blocks (slip gauges) and length bars p. 423
- 21.1.5 Height and depth measurement p. 425
- 21.2 Angle measurement p. 426
- 21.3 Flatness measurement p. 428
- 21.4 Volume measurement p. 428
- 21.5 Viscosity measurement p. 429
- 21.5.1 Capillary and tube viscometers p. 430

- 21.5.2 Falling body viscometer p. 431
- 21.5.3 Rotational viscometers p. 431
- 21.6 Moisture measurement p. 432
- 21.6.1 Industrial moisture measurement techniques p. 432
- 21.6.2 Laboratory techniques for moisture measurement p. 434
- 21.6.3 Humidity measurement p. 435
- 21.7 Sound measurement p. 436
- 21.8 pH measurement p. 437
- 21.8.1 The glass electrode p. 438
- 21.8.2 Other methods of pH measurement p. 439
- 21.9 Gas sensing and analysis p. 439
- 21.9.1 Catalytic (calorimetric) sensors p. 440
- 21.9.2 Paper tape sensors p. 441
- 21.9.3 Liquid electrolyte electrochemical cells p. 441
- 21.9.4 Solid-state electrochemical cells (zirconia sensor) p. 442
- 21.9.5 Catalytic gate FETs p. 442
- 21.9.6 Semiconductor (metal oxide) sensors p. 442
- 21.9.7 Organic sensors p. 442
- 21.9.8 Piezoelectric devices p. 443
- 21.9.9 Infra-red absorption p. 443
- 21.9.10 Mass spectrometers p. 443
- 21.9.11 Gas chromatography p. 443
- References and further reading p. 444
- Appendix 1 Imperial--metric--SI conversion tables p. 445
- Appendix 2 Thevenin's theorem p. 452
- Appendix 3 Thermocouple tables p. 458
- Appendix 4 Solutions to self-test questions p. 464
- Index p. 469