

# Measurement and Instrumentation

## Theory and Application



Alan S. Morris  
Reza Langari



# Contents

<b>Acknowledgement .....</b>	<b>xvii</b>
<b>Preface .....</b>	<b>xix</b>
<b>Chapter 1 Fundamentals of Measurement Systems .....</b>	<b>1</b>
1.1 Introduction.....	1
1.2 Measurement Units.....	2
1.3 Measurement System Design .....	3
1.3.1 Elements of a Measurement System .....	4
1.3.2 Choosing Appropriate Measuring Instruments .....	7
1.4 Measurement System Applications .....	9
1.5 Summary .....	10
1.6 Problems .....	10
<b>Chapter 2 Instrument Types and Performance Characteristics .....</b>	<b>11</b>
2.1 Introduction.....	11
2.2 Review of Instrument Types .....	12
2.2.1 Active and Passive Instruments .....	12
2.2.2 Null-Type and Deflection-Type Instruments.....	14
2.2.3 Analogue and Digital Instruments .....	15
2.2.4 Indicating Instruments and Instruments with a Signal Output.....	16
2.2.5 Smart and Nonsmart Instruments.....	16
2.3 Static Characteristics of Instruments.....	17
2.3.1 Accuracy and Inaccuracy (Measurement Uncertainty) .....	17
2.3.2 Precision/Repeatability/Reproducibility .....	18
2.3.3 Tolerance .....	20
2.3.4 Range or Span .....	20
2.3.5 Linearity.....	20
2.3.6 Sensitivity of Measurement.....	21
2.3.7 Threshold .....	22
2.3.8 Resolution.....	22
2.3.9 Sensitivity to Disturbance .....	22
2.3.10 Hysteresis Effects .....	25
2.3.11 Dead Space.....	26

---

2.4	Dynamic Characteristics of Instruments .....	26
2.4.1	Zero-Order Instrument .....	28
2.4.2	First-Order Instrument.....	28
2.4.3	Second-Order Instrument .....	31
2.5	Necessity for Calibration.....	33
2.6	Summary .....	34
2.7	Problems .....	34
<b>Chapter 3</b>	<b>Measurement Uncertainty.....</b>	<b>39</b>
3.1	Introduction.....	40
3.2	Sources of Systematic Error.....	42
3.2.1	System Disturbance due to Measurement .....	42
3.2.2	Errors due to Environmental Inputs.....	46
3.2.3	Wear in Instrument Components .....	47
3.2.4	Connecting Leads.....	47
3.3	Reduction of Systematic Errors .....	48
3.3.1	Careful Instrument Design.....	48
3.3.2	Calibration .....	48
3.3.3	Method of Opposing Inputs .....	49
3.3.4	High-Gain Feedback .....	49
3.3.5	Signal Filtering.....	51
3.3.6	Manual Correction of Output Reading .....	51
3.3.7	Intelligent Instruments .....	52
3.4	Quantification of Systematic Errors.....	52
3.4.1	Quantification of Individual Systematic Error Components.....	53
3.4.2	Calculation of Overall Systematic Error .....	54
3.5	Sources and Treatment of Random Errors.....	55
3.6	Statistical Analysis of Measurements Subject to Random Errors.....	56
3.6.1	Mean and Median Values .....	56
3.6.2	Standard Deviation and Variance .....	58
3.6.3	Graphical Data Analysis Techniques—Frequency Distributions.....	60
3.6.4	Gaussian (Normal) Distribution.....	63
3.6.5	Standard Gaussian Tables (z Distribution) .....	65
3.6.6	Standard Error of the Mean .....	68
3.6.7	Estimation of Random Error in a Single Measurement .....	69
3.6.8	Distribution of Manufacturing Tolerances .....	70
3.6.9	Chi-Squared ( $\chi^2$ ) Distribution.....	71
3.6.10	Goodness of Fit to a Gaussian Distribution .....	76
3.6.11	Rogue Data Points (Data Outliers) .....	82
3.6.12	Student t Distribution .....	83
3.7	Aggregation of Measurement System Errors.....	88
3.7.1	Combined Effect of Systematic and Random Errors .....	88
3.7.2	Aggregation of Errors from Separate Measurement System Components.....	89
3.7.3	Total Error When Combining Multiple Measurements .....	92

---

3.8 Summary .....	92
3.9 Problems .....	94
<b>Chapter 4 Calibration of Measuring Sensors and Instruments .....</b>	<b>103</b>
4.1 Introduction.....	103
4.2 Principles of Calibration.....	104
4.3 Control of Calibration Environment .....	105
4.4 Calibration Chain and Traceability .....	107
4.5 Calibration Records .....	110
4.6 Summary .....	113
4.7 Problems .....	113
<b>Chapter 5 Data Acquisition with LabVIEW .....</b>	<b>115</b>
5.1 Introduction.....	115
5.2 Computer-Based Data Acquisition.....	116
5.2.1 Acquisition of Data .....	116
5.3 National Instruments LabVIEW.....	117
5.3.1 Virtual Instruments.....	118
5.4 Introduction to Graphical Programming in LabVIEW .....	118
5.4.1 Elements of the Tools Palette .....	120
5.5 Logic Operations in LabVIEW .....	121
5.6 Loops in LabVIEW .....	123
5.7 Case Structure in LabVIEW.....	124
5.8 Data Acquisition Using LabVIEW .....	125
5.9 LabVIEW Function Generation .....	127
5.10 Summary .....	128
5.11 Problems .....	129
5.12 Appendix: Software Tools for Laboratory Data Acquisition .....	132
5.12.1 Measurement Foundry .....	132
5.12.2 DasyLab .....	133
5.12.3 iNET-iWPLUS.....	133
5.12.4 WinWedge .....	133
<b>Chapter 6 Signal Processing with LabVIEW.....</b>	<b>135</b>
6.1 Introduction.....	135
6.2 Analogue Filters .....	136
6.2.1 Passive Filters.....	137
6.2.2 Active Filters Using Op-amps.....	139
6.2.3 Implementation on a Breadboard.....	141
6.2.4 Building the Circuit.....	141
6.2.5 Electronic Components .....	142
6.2.6 Op-amps in Analogue Signal Processing.....	144
6.3 Digital Filters .....	145
6.3.1 Input Averaging Filter.....	145

6.3.2 Filter with Memory .....	146
6.3.3 Example .....	146
6.3.4 LabVIEW Implementation .....	148
6.3.5 Higher Order Digital Filters .....	150
6.4 Conclusions .....	151
6.5 Problems .....	152
6.6 Appendix .....	156
6.6.1 Simple Filter Solution .....	156
6.6.2 Matlab Solution to the Butterworth Filter Design .....	158
<b>Chapter 7 Electrical Indicating and Test Instruments.....</b>	<b>161</b>
7.1 Introduction.....	161
7.2 Digital Meters .....	162
7.2.1 Voltage-to-Time Conversion Digital Voltmeter.....	163
7.2.2 Potentiometric Digital Voltmeter.....	163
7.2.3 Dual-Slope Integration Digital Voltmeter .....	164
7.2.4 Voltage-to-Frequency Conversion Digital Voltmeter .....	164
7.2.5 Digital Multimeter.....	164
7.3 Analogue Meters.....	165
7.3.1 Moving Coil Meter.....	165
7.3.2 Moving Iron Meter.....	167
7.3.3 Clamp-on Meters.....	168
7.3.4 Analogue Multimeter .....	169
7.3.5 Measuring High-Frequency Signals with Analogue Meters .....	169
7.3.6 Calculation of Meter Outputs for Nonstandard Waveforms .....	170
7.4 Oscilloscopes .....	172
7.4.1 Analogue Oscilloscope (Cathode Ray Oscilloscope).....	173
7.4.2 Digital Storage Oscilloscopes .....	177
7.4.3 Digital Phosphor Oscilloscope.....	178
7.4.4 Digital Sampling Oscilloscope .....	179
7.4.5 Personal Computer-Based Oscilloscope .....	180
7.5 Summary .....	180
7.6 Problems .....	181
<b>Chapter 8 Display, Recording, and Presentation of Measurement Data .....</b>	<b>183</b>
8.1 Introduction.....	183
8.2 Display of Measurement Signals .....	184
8.2.1 Electronic Output Displays .....	184
8.2.2 Computer Monitor Displays.....	185
8.3 Recording of Measurement Data .....	185
8.3.1 Chart Recorders .....	185
8.3.2 Ink-Jet and Laser Printers .....	190
8.3.3 Other Recording Instruments .....	190
8.3.4 Digital Data Recorders.....	190

8.4	Presentation of Data .....	191
8.4.1	Tabular Data Presentation .....	191
8.4.2	Graphical Presentation of Data .....	192
8.5	Summary .....	202
8.6	Problems .....	203
<b>Chapter 9 Variable Conversion Elements .....</b>		<b>207</b>
9.1	Introduction.....	208
9.2	Bridge Circuits.....	208
9.2.1	Null-Type d.c. Bridge (Wheatstone Bridge) .....	208
9.2.2	Deflection-Type d.c. Bridge .....	210
9.2.3	Error Analysis .....	218
9.2.4	a.c. Bridges.....	220
9.2.5	Commercial Bridges.....	226
9.3	Resistance Measurement .....	226
9.3.1	d.c. Bridge Circuit.....	226
9.3.2	Voltmeter–Ammeter Method .....	227
9.3.3	Resistance–Substitution Method .....	227
9.3.4	Use of Digital Voltmeter to Measure Resistance.....	228
9.3.5	Ohmmeter .....	228
9.4	Inductance Measurement .....	229
9.5	Capacitance Measurement.....	229
9.6	Current Measurement .....	230
9.7	Frequency Measurement.....	232
9.7.1	Digital Counter/Timer.....	232
9.7.2	Phase-Locked Loop.....	233
9.7.3	Oscilloscope .....	234
9.7.4	Wien Bridge .....	235
9.8	Phase Measurement .....	236
9.8.1	Electronic Counter/Timer.....	236
9.8.2	X–Y Plotter .....	237
9.8.3	Oscilloscope .....	237
9.8.4	Phase-Sensitive Detector.....	238
9.9	Summary .....	238
9.10	Problems .....	239
<b>Chapter 10 Measurement Signal Transmission .....</b>		<b>245</b>
10.1	Introduction.....	245
10.2	Electrical Transmission .....	246
10.2.1	Transmission as Varying Voltages.....	246
10.2.2	Current Loop Transmission.....	247
10.2.3	Transmission Using an a.c. Carrier.....	248
10.3	Pneumatic Transmission.....	250
10.4	Fiber-Optic Transmission .....	250
10.4.1	Principles of Fiber Optics.....	251

10.4.2	Transmission Characteristics .....	254
10.4.3	Multiplexing Schemes .....	256
10.5	Optical Wireless Telemetry .....	257
10.6	Radiotelemetry (Radio Wireless Transmission) .....	258
10.7	Digital Transmission Protocols .....	260
10.8	Summary .....	261
10.9	Problems .....	263
<b>Chapter 11</b>	<b><i>Intelligent Devices</i></b> .....	<b>265</b>
11.1	Introduction.....	265
11.2	Principles of Digital Computation .....	266
11.2.1	Elements of a Computer.....	266
11.2.2	Computer Operation .....	269
11.2.3	Computer Input–Output Interface .....	270
11.2.4	Practical Considerations in Adding Computers to Measurement Systems.....	273
11.3	Intelligent Devices .....	274
11.3.1	Intelligent Instruments.....	274
11.3.2	Smart Sensors .....	276
11.3.3	Smart Transmitters .....	278
11.4	Communication with Intelligent Devices .....	280
11.4.1	Input–Output Interface .....	281
11.4.2	Parallel Data Bus.....	282
11.4.3	Local Area Networks.....	283
11.4.4	Digital Fieldbuses .....	285
11.5	Summary .....	287
11.6	Problems .....	288
<b>Chapter 12</b>	<b><i>Measurement Reliability and Safety Systems</i></b> .....	<b>291</b>
12.1	Introduction.....	291
12.2	Reliability .....	293
12.2.1	Principles of Reliability.....	293
12.2.2	Laws of Reliability in Complex Systems .....	298
12.2.3	Improving Measurement System Reliability .....	300
12.2.4	Software Reliability.....	302
12.3	Safety Systems.....	307
12.3.1	Introduction to Safety Systems .....	308
12.3.2	Design of a Safety System .....	309
12.4	Summary .....	313
12.5	Problems .....	314
<b>Chapter 13</b>	<b><i>Sensor Technologies</i></b> .....	<b>317</b>
13.1	Introduction.....	318
13.2	Capacitive Sensors.....	318
13.3	Resistive Sensors .....	319

13.4	Magnetic Sensors.....	319
13.5	Hall-Effect Sensors.....	321
13.6	Piezoelectric Transducers.....	322
13.7	Strain Gauges.....	323
13.8	Piezoresistive Sensors.....	324
13.9	Optical Sensors.....	324
13.9.1	Optical Sensors (Air Path).....	325
13.9.2	Optical Sensors (Fiber Optic).....	326
13.10	Ultrasonic Transducers.....	332
13.10.1	Transmission Speed.....	333
13.10.2	Directionality of Ultrasound Waves.....	334
13.10.3	Relationship Between Wavelength, Frequency, and Directionality of Ultrasound Waves.....	335
13.10.4	Attenuation of Ultrasound Waves.....	335
13.10.5	Ultrasound as a Range Sensor.....	336
13.10.6	Effect of Noise in Ultrasonic Measurement Systems.....	337
13.10.7	Exploiting Doppler Shift in Ultrasound Transmission.....	338
13.11	Nuclear Sensors.....	340
13.12	Microsensors.....	340
13.13	Summary.....	342
13.14	Problems.....	345
<b>Chapter 14 Temperature Measurement.....</b>		<b>347</b>
14.1	Introduction.....	348
14.2	Thermoelectric Effect Sensors (Thermocouples).....	349
14.2.1	Thermocouple Tables.....	354
14.2.2	Nonzero Reference Junction Temperature.....	354
14.2.3	Thermocouple Types.....	357
14.2.4	Thermocouple Protection.....	359
14.2.5	Thermocouple Manufacture.....	360
14.2.6	Thermopile.....	361
14.2.7	Digital Thermometer.....	361
14.2.8	Continuous Thermocouple.....	361
14.3	Varying Resistance Devices.....	362
14.3.1	Resistance Thermometers (Resistance Temperature Devices).....	363
14.3.2	Thermistors.....	364
14.4	Semiconductor Devices.....	366
14.5	Radiation Thermometers.....	366
14.5.1	Optical Pyrometer.....	368
14.5.2	Radiation Pyrometers.....	369
14.6	Thermography (Thermal Imaging).....	373
14.7	Thermal Expansion Methods.....	375
14.7.1	Liquid-in-Glass Thermometers.....	375
14.7.2	Bimetallic Thermometer.....	376
14.7.3	Pressure Thermometers.....	377



14.8	Quartz Thermometers.....	377
14.9	Fiber-Optic Temperature Sensors .....	378
14.10	Color Indicators .....	379
14.11	Change of State of Materials.....	380
14.12	Intelligent Temperature-Measuring Instruments.....	380
14.13	Choice between Temperature Transducers .....	381
14.14	Calibration of Temperature Transducers .....	383
	14.14.1 Reference Instruments and Special Calibration Equipment.....	384
	14.14.2 Calculating Frequency of Calibration Checks .....	386
	14.14.3 Procedures for Calibration.....	387
14.15	Summary .....	389
14.16	Problems .....	392
<b>Chapter 15 Pressure Measurement.....</b>		<b>397</b>
15.1	Introduction.....	398
15.2	Diaphragms.....	399
15.3	Capacitive Pressure Sensor .....	401
15.4	Fiber-Optic Pressure Sensors .....	401
15.5	Bellows .....	402
15.6	Bourdon Tube .....	403
15.7	Manometers .....	405
	15.7.1 U-Tube Manometer .....	405
	15.7.2 Well-Type Manometer (Cistern Manometer) .....	406
	15.7.3 Inclined Manometer (Draft Gauge).....	407
15.8	Resonant Wire Devices .....	407
15.9	Electronic Pressure Gauges .....	408
15.10	Special Measurement Devices for Low Pressures.....	408
	15.10.1 Thermocouple Gauge .....	409
	15.10.2 Thermistor Gauge .....	410
	15.10.3 Pirani Gauge .....	410
	15.10.4 McLeod Gauge .....	410
	15.10.5 Ionization Gauge.....	412
15.11	High-Pressure Measurement (Greater than 7000 bar).....	412
15.12	Intelligent Pressure Transducers .....	412
15.13	Differential Pressure-Measuring Devices .....	413
15.14	Selection of Pressure Sensors .....	414
15.15	Calibration of Pressure Sensors .....	415
	15.15.1 Reference Calibration Instruments .....	416
	15.15.2 Calculating Frequency of Calibration Checks.....	419
	15.15.3 Procedures for Calibration .....	420
15.16	Summary .....	421
15.17	Problems .....	422
<b>Chapter 16 Flow Measurement .....</b>		<b>425</b>
16.1	Introduction.....	426
16.2	Mass Flow Rate .....	427

16.2.1	Conveyor-Based Methods .....	427
16.2.2	Coriolis Flowmeter .....	427
16.2.3	Thermal Mass Flow Measurement .....	429
16.2.4	Joint Measurement of Volume Flow Rate and Fluid Density .....	429
16.3	Volume Flow Rate .....	429
16.3.1	Differential Pressure (Obstruction-Type) Meters .....	430
16.3.2	Variable Area Flowmeters (Rotameters) .....	435
16.3.3	Positive Displacement Flowmeters .....	436
16.3.4	Turbine Meters .....	438
16.3.5	Electromagnetic Flowmeters .....	439
16.3.6	Vortex-Shedding Flowmeters .....	441
16.3.7	Ultrasonic Flowmeters .....	442
16.3.8	Other Types of Flowmeters for Measuring Volume Flow Rate .....	447
16.3.9	Open Channel Flowmeters .....	449
16.4	Intelligent Flowmeters .....	449
16.5	Choice between Flowmeters for Particular Applications .....	450
16.6	Calibration of Flowmeters .....	451
16.6.1	Calibration Equipment and Procedures for Mass Flow-Measuring Instruments .....	452
16.6.2	Calibration Equipment and Procedures for Instruments Measuring Volume Flow Rate of Liquids .....	452
16.6.3	Calibration Equipment and Procedures for Instruments Measuring Volume Flow Rate of Gases .....	456
16.6.4	Reference Standards .....	457
16.7	Summary .....	457
16.8	Problems .....	459
<b>Chapter 17 Level Measurement.....</b>		<b>461</b>
17.1	Introduction .....	461
17.2	Dipsticks .....	462
17.3	Float Systems .....	462
17.4	Pressure-Measuring Devices (Hydrostatic Systems) .....	463
17.5	Capacitive Devices .....	464
17.6	Ultrasonic Level Gauge .....	465
17.7	Radar (Microwave) Sensors .....	467
17.8	Nucleonic (or Radiometric) Sensors .....	468
17.9	Other Techniques .....	469
17.9.1	Vibrating Level Sensor .....	469
17.9.2	Laser Methods .....	470
17.10	Intelligent Level-Measuring Instruments .....	470
17.11	Choice between Different Level Sensors .....	470
17.12	Calibration of Level Sensors .....	472
17.13	Summary .....	473
17.14	Problems .....	475

<b>Chapter 18 Mass, Force, and Torque Measurement.....</b>	<b>477</b>
18.1 Introduction.....	478
18.2 Mass (Weight) Measurement .....	478
18.2.1 Electronic Load Cell (Electronic Balance) .....	479
18.2.2 Pneumatic and Hydraulic Load Cells .....	481
18.2.3 Intelligent Load Cells .....	482
18.2.4 Mass Balance (Weighing) Instruments .....	483
18.2.5 Spring Balance.....	486
18.3 Force Measurement .....	487
18.3.1 Use of Accelerometers .....	487
18.3.2 Vibrating Wire Sensor.....	487
18.3.3 Use of Load Cells.....	488
18.4 Torque Measurement.....	488
18.4.1 Measurement of Induced Strain .....	488
18.4.2 Optical Torque Measurement.....	489
18.4.3 Reaction Forces in Shaft Bearings.....	489
18.4.4 Prony Brake .....	491
18.5 Calibration of Mass, Force, and Torque Measuring Sensors .....	492
18.5.1 Mass Calibration.....	493
18.5.2 Force Sensor Calibration.....	494
18.5.3 Calibration of Torque Measuring Systems .....	494
18.6 Summary .....	495
18.7 Problems .....	496
<b>Chapter 19 Translational Motion, Vibration, and Shock Measurement.....</b>	<b>497</b>
19.1 Introduction.....	498
19.2 Displacement .....	498
19.2.1 Resistive Potentiometer .....	499
19.2.2 Linear Variable Differential Transformer (LVDT) .....	502
19.2.3 Variable Capacitance Transducers .....	504
19.2.4 Variable Inductance Transducers .....	505
19.2.5 Strain Gauges.....	506
19.2.6 Piezoelectric Transducers.....	506
19.2.7 Nozzle Flapper.....	507
19.2.8 Other Methods of Measuring Small/Medium-Sized Displacements.....	509
19.2.9 Measurement of Large Displacements (Range Sensors).....	513
19.2.10 Proximity Sensors.....	516
19.2.11 Choosing Translational Measurement Transducers.....	516
19.2.12 Calibration of Translational Displacement Measurement Transducers .....	517
19.3 Velocity.....	518
19.3.1 Differentiation of Displacement Measurements .....	518
19.3.2 Integration of Output of an Accelerometer.....	518
19.3.3 Conversion to Rotational Velocity.....	518
19.3.4 Calibration of Velocity Measurement Systems .....	518

---

19.4	Acceleration .....	519
19.4.1	Selection of Accelerometers .....	521
19.4.2	Calibration of Accelerometers .....	521
19.5	Vibration .....	522
19.5.1	Nature of Vibration .....	522
19.5.2	Vibration Measurement .....	523
19.5.3	Calibration of Vibration Sensors.....	525
19.6	Shock .....	525
19.6.1	Calibration of Shock Sensors .....	526
19.7	Summary .....	526
19.8	Problems .....	528
<b>Chapter 20</b>	<b>Rotational Motion Transducers .....</b>	<b>529</b>
20.1	Introduction.....	530
20.2	Rotational Displacement .....	530
20.2.1	Circular and Helical Potentiometers .....	530
20.2.2	Rotational Differential Transformer.....	531
20.2.3	Incremental Shaft Encoders .....	532
20.2.4	Coded Disc Shaft Encoders .....	534
20.2.5	The Resolver.....	538
20.2.6	The Synchro.....	540
20.2.7	The Induction Potentiometer .....	543
20.2.8	The Rotary Inductosyn .....	543
20.2.9	Gyroscopes.....	543
20.2.10	Choice between Rotational Displacement Transducers.....	548
20.2.11	Calibration of Rotational Displacement Transducers.....	549
20.3	Rotational Velocity.....	549
20.3.1	Digital Tachometers .....	549
20.3.2	Stroboscopic Methods .....	552
20.3.3	Analogue Tachometers .....	553
20.3.4	The Rate Gyroscope .....	555
20.3.5	Fiber-Optic Gyroscope .....	557
20.3.6	Differentiation of Angular Displacement Measurements.....	557
20.3.7	Integration of Output from an Accelerometer .....	558
20.3.8	Choice between Rotational Velocity Transducers.....	558
20.3.9	Calibration of Rotational Velocity Transducers .....	558
20.4	Rotational Acceleration .....	558
20.4.1	Calibration of Rotational Accelerometers.....	559
20.5	Summary .....	559
20.6	Problems .....	560
<b>Appendix 1</b>	<b>Imperial-Metric-SI Conversion Tables .....</b>	<b>561</b>
<b>Appendix 2</b>	<b>Thévenin's Theorem.....</b>	<b>569</b>
<b>Appendix 3</b>	<b>Thermocouple Tables .....</b>	<b>575</b>
<b>Index</b>	<b>.....</b>	<b>581</b>