

Measurement and Instrumentation

Theory and Application



Alan S. Morris
Reza Langari



Contents

Acknowledgement	xvii
Preface	xix
Chapter 1 Fundamentals of Measurement Systems	1
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
Chapter 2 Instrument Types and Performance Characteristics	11
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
Chapter 3	Measurement Uncertainty.....	39
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 (χ^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
Chapter 4 Calibration of Measuring Sensors and Instruments	103
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
Chapter 5 Data Acquisition with LabVIEW	115
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
Chapter 6 Signal Processing with LabVIEW.....	135
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
Chapter 7 Electrical Indicating and Test Instruments.....	161
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
Chapter 8 Display, Recording, and Presentation of Measurement Data	183
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
Chapter 9	Variable Conversion Elements	207
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
Chapter 10	Measurement Signal Transmission	245
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
Chapter 11	Intelligent Devices.....	265
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
Chapter 12	Measurement Reliability and Safety Systems.....	291
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
Chapter 13	Sensor Technologies	317
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
Chapter 14	Temperature Measurement.....	347
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
Chapter 15	Pressure Measurement.....	397
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
Chapter 16	Flow Measurement	425
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
Chapter 17	Level Measurement	461
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

Chapter 18 Mass, Force, and Torque Measurement.....	477
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
 Chapter 19 Translational Motion, Vibration, and Shock Measurement.....	 497
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
Chapter 20 Rotational Motion Transducers	529
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
Appendix 1 Imperial-Metric-SI Conversion Tables	561
Appendix 2 Thévenin's Theorem	569
Appendix 3 Thermocouple Tables	575
Index	581