
Contents

1 Fundamentals of Experimentation	1
1.1 Introduction	1
2 Experiments	5
2.1 Chapter Overview	5
2.2 Experimental Approach	6
2.3 Role of Experiments	7
2.4 The Experiment	9
2.5 Classification of Experiments	12
2.6 Plan for Successful Experimentation	13
2.7 Hypothesis Testing*	14
2.8 Design of Experiments*	18
2.9 Factorial Design*	20
2.10 Problems	24
Bibliography	27
3 Fundamental Electronics	29
3.1 Chapter Overview	30
3.2 Concepts and Definitions	30
3.2.1 Charge	30
3.2.2 Current	31
3.2.3 Force	33
3.2.4 Field	33
3.2.5 Potential	33
3.2.6 Resistance and Resistivity	33
3.2.7 Power	34
3.2.8 Capacitance	34
3.2.9 Inductance	35
3.3 Circuit Elements	35
3.3.1 Resistor	36
3.3.2 Capacitor	36
3.3.3 Inductor	36
3.3.4 Transistor	37
3.3.5 Voltage Source	38
3.3.6 Current Source	38
3.4 RLC Combinations	39

3.5	Elementary DC Circuit Analysis	42
3.5.1	Voltage Divider	42
3.5.2	Electric Motor with Battery	43
3.5.3	Wheatstone Bridge	45
3.6	Elementary AC Circuit Analysis	48
3.7	Equivalent Circuits*	51
3.8	Meters*	54
3.9	Impedance Matching and Loading Error*	55
3.10	Electrical Noise*	58
3.11	Problems	60
	Bibliography	71
4	Measurement Systems: Sensors and Transducers	73
4.1	Chapter Overview	74
4.2	Measurement System Overview	74
4.3	Sensor Domains	76
4.4	Sensor Characteristics	78
4.5	Physical Principles of Sensors	80
4.6	Electric	83
4.6.1	Resistive	83
4.6.2	Capacitive	94
4.6.3	Inductive	99
4.7	Piezoelectric	102
4.8	Fluid Mechanic	106
4.9	Optic	111
4.10	Photoelastic	127
4.11	Thermoelectric	129
4.12	Electrochemical	131
4.13	Sensor Scaling*	135
4.14	Problems	139
	Bibliography	143
5	Measurement Systems: Other Components	145
5.1	Chapter Overview	145
5.2	Signal Conditioning, Processing, and Recording	146
5.3	Amplifiers	146
5.4	Filters	152
5.5	Analog-to-Digital Converters	158
5.6	Smart Measurement Systems	164
5.6.1	Sensors and Microcontroller Platforms	166
5.6.2	Arduino Microcontrollers	166
5.6.3	Wireless Transmission of Data	168
5.6.4	Using the MATLAB Programming Environment	172
5.6.5	Examples of Arduino Programming using Simulink	173

5.7 Other Example Measurement Systems	178
5.8 Problems	186
Bibliography	195
6 Measurement Systems: Calibration and Response	197
6.1 Chapter Overview	197
6.2 Static Response Characterization by Calibration	198
6.3 Dynamic Response Characterization	203
6.4 Zero-Order System Dynamic Response	205
6.5 First-Order System Dynamic Response	206
6.5.1 Response to Step-Input Forcing	207
6.5.2 Response to Sinusoidal-Input Forcing	210
6.6 Second-Order System Dynamic Response	218
6.6.1 Response to Step-Input Forcing	220
6.6.2 Response to Sinusoidal-Input Forcing	224
6.7 Measurement System Dynamic Response	225
6.8 Problems	228
Bibliography	235
7 Measurement Systems: Design-Stage Uncertainty	237
7.1 Chapter Overview	237
7.2 Design-Stage Uncertainty Analysis	238
7.3 Design-Stage Uncertainty Estimate of a Measurand	238
7.4 Design-Stage Uncertainty Estimate of a Result	244
7.5 Problems	251
Bibliography	257
8 Signal Characteristics	259
8.1 Chapter Overview	259
8.2 Signal Classification	260
8.3 Signal Variables	263
8.4 Signal Statistical Parameters	267
8.5 Problems	272
Bibliography	275
9 The Fourier Transform	277
9.1 Chapter Overview	277
9.2 Fourier Series of a Periodic Signal	277
9.3 Complex Numbers and Waves	285
9.4 Exponential Fourier Series	287
9.5 Spectral Representations	289
9.6 Continuous Fourier Transform	291

9.7 Continuous Fourier Transform Properties*	294
9.8 Discrete Fourier Transform	295
9.9 Fast Fourier Transform	298
9.10 Problems	302
Bibliography	305
10 Digital Signal Analysis	307
10.1 Chapter Overview	307
10.2 Digital Sampling	308
10.3 Digital Sampling Errors	309
10.3.1 Aliasing	310
10.3.2 Amplitude Ambiguity	314
10.4 Windowing*	324
10.5 Determining a Sample Period	328
10.6 Problems	333
Bibliography	337
11 Probability	339
11.1 Chapter Overview	340
11.2 Relation to Measurements	340
11.3 Basic Probability Concepts	341
11.3.1 Union and Intersection of Sets	341
11.3.2 Conditional Probability	343
11.4 Sample versus Population	347
11.5 Plotting Statistical Information	348
11.6 Probability Density Function	357
11.7 Various Probability Density Functions	362
11.7.1 Binomial Distribution	364
11.7.2 Poisson Distribution	365
11.8 Central Moments	367
11.9 Probability Distribution Function	371
11.10 Problems	373
Bibliography	379
12 Statistics	381
12.1 Chapter Overview	381
12.2 Normal Distribution	382
12.3 Normalized Variables	385
12.4 Student's <i>t</i> Distribution	390
12.5 Rejection of Data	397
12.5.1 Single-Variable Outlier Determination	398
12.5.2 Paired-Variable Outlier Determination	399
12.6 Standard Deviation of the Means	401

12.7 Chi-Square Distribution	404
12.7.1 Estimating the True Variance	408
12.7.2 Establishing a Rejection Criterion	409
12.7.3 Comparing Observed and Expected Distributions	410
12.8 Pooling Samples*	412
12.9 Problems	415
Bibliography	423
13 Uncertainty Analysis	425
13.1 Chapter Overview	426
13.2 Modeling and Experimental Uncertainties	426
13.3 Probabilistic Basis of Uncertainty	429
13.4 Identifying Sources of Error	431
13.5 Systematic and Random Errors	432
13.6 Quantifying Systematic and Random Errors	434
13.7 Measurement Uncertainty Analysis	436
13.8 Uncertainty Analysis of a Multiple-Measurement Result	438
13.9 Uncertainty Analyses for Other Measurement Situations	443
13.10 Uncertainty Analysis Summary	447
13.11 Finite-Difference Uncertainties*	450
13.11.1 Derivative Approximation*	450
13.11.2 Integral Approximation*	453
13.11.3 Uncertainty Estimate Approximation*	457
13.12 Uncertainty Based upon Interval Statistics*	459
13.13 Problems	462
Bibliography	473
14 Regression and Correlation	475
14.1 Chapter Overview	476
14.2 Least-Squares Approach	476
14.3 Least-Squares Regression Analysis	477
14.4 Linear Analysis	479
14.5 Higher-Order Analysis*	483
14.6 Multi-Variable Linear Analysis*	487
14.7 Determining the Appropriate Fit	489
14.8 Regression Confidence Intervals	495
14.9 Regression Parameters	502
14.10 Linear Correlation Analysis	506
14.11 Signal Correlations in Time*	513
14.11.1 Autocorrelation*	513
14.11.2 Cross-Correlation*	516
14.12 Problems	522
Bibliography	527

15 Units and Significant Figures	529
15.1 Chapter Overview	530
15.2 English and Metric Systems	530
15.3 Systems of Units	532
15.4 SI Standards	537
15.5 Technical English and SI Conversion Factors	539
15.5.1 Length	539
15.5.2 Area and Volume	540
15.5.3 Density	540
15.5.4 Mass and Weight	540
15.5.5 Force	542
15.5.6 Work and Energy	543
15.5.7 Power	543
15.5.8 Light Radiation	543
15.5.9 Temperature	546
15.5.10 Other Properties	547
15.6 Prefixes	549
15.7 Significant Figures	550
15.8 Problems	554
Bibliography	559
16 Technical Communication	561
16.1 Chapter Overview	561
16.2 Guidelines for Writing	562
16.2.1 Writing in General	562
16.2.2 Writing Technical Memoranda	563
16.2.3 Number and Unit Formats	565
16.2.4 Graphical Presentation	566
16.3 Technical Memo	573
16.4 Technical Report	574
16.5 Oral Technical Presentation	576
16.6 Problems	579
Bibliography	581
A Glossary	583
B Symbols	597
C Review Problem Answers	607
Index	609