

Principles of
Industrial
Measurement

for Control Applications

Ernest Smith

IBM United Kingdom Limited



INSTRUMENT SOCIETY OF AMERICA

Contents

Preface	v
List of Symbols	<i>ix</i>
1 The Development of Industrial Instrumentation	3
Introduction	3
In the Beginning	4
Instrumentation in Early Civilizations	5
Modern Industrial Instrumentation	6
Process Control	7
Automatic Control	7
Electrical Instrumentation	8
Chart Recorders	8
The Process Control Computer	9
The Present	11
2 Introduction to Sensor Fundamentals	13
Sensors and Transducers	13
Terminology	14
Sensors in the Industrial Environment	18
3 Basic Electrical Theory	21

Ohm's Law	21	
Resistances in Series	21	
Resistances in Parallel	22	
Power in a Circuit	23	
Resistivity	23	
Effect of Temperature on Resistance	23	
The Potentiometer	24	
Faraday's Law	31	
Electromagnetism	32	
Inductance in AC Circuits	36	
Lenz's Law	38	
AC Bridges	40	
Capacitance in Circuits	43	
Inductance and Capacitance in an AC Circuit	50	
Capacitors as Transducers	53	
RC Filters	55	
Comment on Units	57	
4 Strain Gage Theory		59
Mechanical Strain	59	
Electrical Strain	61	
Gage Factor	61	
The Practical Strain Gage	63	
Strain Gage Bridges	65	
Circuits for Strain-Gage Measurements	67	
Four-Arm Bridges	70	
Zero Methods of Strain Measurement	71	
Deflection Method of Strain Measurement	74	
Bridge Sensitivity Factor	75	
Effects of Temperature on Strain Gages	75	
Semiconductor Strain Gages	77	
5 Pressure Measurement		83
Relationship Between Force and Pressure	83	
Atmospheric Pressure	84	
Absolute, Gage, and Differential Pressures	84	
Primary Transducers for Pressure Measurement	86	

Secondary Transducers	89	
Modern Pressure Sensors	92	
Pressure Surge Damping	99	
Pressure Multiplexing	100	
6 Temperature Measurement		103
Temperature Scales	103	
Expansion Thermometers	105	
Mercury-in-Steel Thermometer	105	
Change-of-State Thermometers	107	
Resistance Thermometers	108	
Self-Heating of Resistance Sensors	111	
Thermal Time Constant	112	
Thermocouples	112	
Common and Series Mode Voltages	115	
Thermocouple Transmitters	117	
Industrial Thermocouples	118	
Thermopiles	119	
Thermistors	120	
Thermostats	121	
7 Displacement Measurement		123
Linear Variable Differential Transformer	123	
DC-to-DC LVDTs	129	
Digital Displacement Sensors	131	
Binary Coded Signals	131	
Digitizers	138	
Optical Digitizers	142	
Inductive Digitizers	147	
Linear Displacement Digitizers	147	
Magnetic Tape Digitizers	147	
Hoop Pickups	147	
8 Load Measurement		149
Load Cells	149	
Load Cell Design	152	
Load Cells with Differential Transformer Sensors	153	

	In-Line Weighing	158
	In-Line Package Weighing	158
	In-Line Product Weighing	160
	Rate Weighers	166
	Load Measurement in the Steel Industry	168
9	Flow Measurement	171
	Flow Meters	171
	Positive-Displacement Meters	172
	Restriction Flow Meters	172
	The Turbine Flow Meter	179
	Electromagnetic Flow Meter	180
	Variable Area Flow Meters	180
	Ultrasonic Flow Meters	183
	Anemometers	183
10	Torque Measurement	185
	Torque Measurement with Strain Gages	185
	Torque Measurement with Strain Gage on Rotating Shafts	187
	Torque Measurement by Phase Measurement	192
11	Level Measurement	193
	Sight Glasses	193
	Float Systems	194
	Pressure Methods of Level Measurement	196
	Capacitance Methods of Level Measurement	198
	Level Switching	200
	Measurement of the Level of Solids in Tanks	201
12	Miscellaneous Properties of Materials	203
	Humidity Measurement	203
	pH Measurement	205
	Density Measurement	209
	Specific Gravity Measurement	209
	Viscosity Measurement	210
	Carbon Dioxide Measurement	211
	Component Gas Analysis	211

13	Vibration Measurement	213
	Simple Harmonic Motion	213
	Damped Harmonic Motion	217
	Forced Vibration of a Simple System	221
	Vibration Measurement Instrument Theory	225
	Vibration Measuring Transducers	229
	Making Vibration Measurements	232
	Complex Motion	232
	Seismology	233
	Accelerometer Measurements	239
	Strain-Gaged Accelerometers	239
	Calibration of Accelerometers	241
	Piezoelectric Accelerometers	242
	Analysis of Vibration Records	247
	Application of Analysis Technique	251
	Resonance Testing	254
	Exciters	256
	Ground-Referenced Resonance Tests	261
14	Recording Techniques	267
	Analog Recorders	267
	Pen Recorders	268
	Servo Recorders	269
	Multiplexing Recorder Signals	269
	Galvanometer Recorders	274
	Ink Jet Recorders	277
	Magnetic Tape Recording	277
	FM Recording	287
	Multichannel Recording	288
	Pulse Duration Recording	289
	Digital Recording	295
	Character Printers	296
	Data Logging	297
	Paper Tape Punches	299
	Parity Checks	300
	xy Plotters	300

	Multiplexers	302	
	Analog-to-Digital Conversion	311	
15	Calibration Techniques		317
	Calibration of Site Equipment	318	
	Pressure Standards	320	
	Sensitivity Considerations	324	
	Temperature Effects on Sensitivity and Zero	327	
	Calibration of Other Sensors	330	
	Temperature Calibrations	330	
	Calibration of Vibration Sensors	335	
	Accelerometer Calibration Rigs	336	
	Calculating Calibration Factors Mathematically	342	
16	The Computer		345
	Binary Notation and Arithmetic	346	
	Binary Adder	348	
	Instructions	350	
	Computer Functional Units	351	
	Input and Output Units	354	
	Programming the Computer	358	
	Applying Computers to Industrial Operations	360	
	Cyclic Machine Monitoring	361	
	Power Demand Control	366	
	Peak Power Demand Meters	366	
	Predictive Control	366	
	Computer Control of Peak Power Demand	367	
	Designing a Control Strategy	368	
17	Electrical Interfacing		373
	Electrical Interference and Cabling	373	
	Cable Types	378	
	Interfacing in Hazardous Environments	380	
	Interfacing with Integrated Circuits	386	
	Operational Amplifiers	386	
	Application of Operational Amplifiers	388	
	Power Supplies for Operational Amplifiers	390	

Integrated Time-Out Circuits	391
Input Protection	394
Interfacing to Computers	394
CAMAC Interface	396
IEEE 488 Interface	398
Serial Transmission Systems	398
Transmission of Signals Over Telephone Lines	401
Automatic Calling Circuits	403
Digital Input	405
Digital Output	412
Analog Input	415
Analog Output	415
Appendix. Instrument Society of America Standards and Recommended Practices	417
Index	427