

Fourth Edition

**MEASUREMENT
SYSTEMS**
APPLICATION AND DESIGN

Ernest O. Doebelin

CONTENTS

Preface to the Fourth Edition	xiii
Preface to the Third Edition	xv
Preface to the Revised Edition	xvii
Preface to the First Edition	xix

Part 1 General Concepts

1	Types of Applications of Measurement Instrumentation	3
1.1	Introduction	3
1.2	Monitoring of Processes and Operations	3
1.3	Control of Processes and Operations	4
1.4	Experimental Engineering Analysis	5
1.5	Computer-Aided Machines and Processes	6
1.6	Conclusion	6
	Problems	8
	Bibliography	9
2	Generalized Configurations and Functional Descriptions of Measuring Instruments	10
2.1	Functional Elements of an Instrument	10
2.2	Active and Passive Transducers	15
2.3	Analog and Digital Modes of Operation	17
2.4	Null and Deflection Methods	18
2.5	Input-Output Configuration of Measuring Instruments and Instrument Systems	19
	Methods of Correction for Interfering and Modifying Inputs	
2.6	Conclusion	35
	Problems	36

3	Generalized Performance Characteristics of Instruments	37
3.1	Introduction	37
3.2	Static Characteristics	38
	Meaning of Static Calibration. Accuracy, Precision, and Bias. Combination of Component Errors in Overall System-Accuracy Calculations. Addition. Subtraction. Multiplication and Division. Static Sensitivity. Linearity. Threshold, Resolution, Hysteresis, and Dead Space. Scale Readability. Span. Generalized Static Stiffness and Input Impedance. Computer-Aided Calibration and Measurement; Multiple Regression. Concluding Remarks on Static Characteristics.	
3.3	Dynamic Characteristics	94
	Generalized Mathematical Model of Measurement System. Digital Simulation Methods for Dynamic Response Analysis. Operational Transfer Function. Sinusoidal Transfer Function. Zero-Order Instrument. First-Order Instrument. Step Response of First-Order Instruments. Ramp Response of First-Order Instruments. Frequency Response of First-Order Instruments. Impulse Response of First-Order Instruments. Second-Order Instrument. Step Response of Second-Order Instruments. Terminated-Ramp Response of Second-Order Instruments. Ramp Response of Second-Order Instruments. Frequency Response of Second-Order Instruments. Impulse Response of Second-Order Instruments. Dead-Time Elements. Logarithmic Plotting of Frequency-Response Curves. Response of a General Form of Instrument to a Periodic Input. Response of a General Form of Instrument to a Transient Input. Frequency Spectra of Amplitude-Modulated Signals. Characteristics of Random Signals. Requirements on Instrument Transfer Function to Ensure Accurate Measurement. Numerical Correction of Dynamic Data. Experimental Determination of Measurement-System Parameters. Loading Effects under Dynamic Conditions.	
	Problems	98
	Bibliography	202

Part 2 Measuring Devices

4	Motion and Dimensional Measurement	207
4.1	Introduction	207
4.2	Fundamental Standards	208
4.3	Relative Displacement, Translational and Rotational.	210
	Calibration. Resistive Potentiometers. Resistance Strain Gages. Differential Transformers. Synchros and Induction Potentiometers. Variable-Inductance and Variable-Reluctance Pickups. Eddy-Current Noncontacting Transducers. Capacitance Pickups. Piezoelectric Transducers. Electro-Optical Devices. Photographic, Videotape, and Holographic Techniques. Photoelastic, Brittle-Coating and	

	Moiré Fringe Stress-Analysis Techniques. Displacement-to-Pressure (Nozzle-Flapper) Transducer. Digital Displacement Transducers (Translational and Rotary Encoders). Ultrasonic Transducers.	
4.4	Relative Velocity, Translational and Rotational. Calibration. Velocity by Electrical Differentiation of Displacement Voltage Signals. Average Velocity from Measured Δx and Δt . Mechanical Flyball Angular-Velocity Sensor. Mechanical Revolution Counters and Timers. Magnetic and Photoelectric Pulse-Counting Methods. Stroboscopic Methods. Translational-Velocity Transducers (Moving-Coil and Moving-Magnet Pickups). DC Tachometer Generators for Rotary-Velocity Measurement. AC Tachometer Generators for Rotary-Velocity Measurement. Eddy-Current Drag-Cup Tachometer.	308
4.5	Relative-Acceleration Measurements	319
4.6	Seismic- (Absolute-) Displacement Pickups	320
4.7	Seismic- (Absolute-) Velocity Pickups	322
4.8	Seismic- (Absolute-) Acceleration Pickups (Accelerometers) Deflection-Type Accelerometers. Null-Balance- (Servo-) Type Accelerometers. Accelerometers for Inertial Navigation. Mechanical Loading of Accelerometers on the Test Object.	323
4.9	Calibration of Vibration Pickups	336
4.10	Jerk Pickups	339
4.11	Pendulous (Gravity-Referenced) Angular-Displacement Sensors	341
4.12	Gyroscopic (Absolute) Angular-Displacement and Velocity Sensors	345
4.13	Coordinate-Measuring Machines	355
4.14	Surface-Finish Measurement	364
4.15	Machine Vision	371
	Problems	383
	Bibliography	389
5	Force, Torque, and Shaft Power Measurement	390
5.1	Standards and Calibration	390
5.2	Basic Methods of Force Measurement	392
5.3	Characteristics of Elastic Force Transducers Bonded-Strain-Gage Transducers. Differential-Transformer Transducers. Piezoelectric Transducers. Variable-Reluctance/FM-Oscillator Digital Systems. Loading Effects.	397
5.4	Resolution of Vector Forces and Moments into Rectangular Components	410
5.5	Torque Measurement on Rotating Shafts	416
5.6	Shaft Power Measurement (Dynamometers)	425
5.7	Gyroscopic Force and Torque Measurement	429
5.8	Vibrating-Wire Force Transducers	432
	Problems	433
	Bibliography	436
6	Pressure and Sound Measurement	437
6.1	Standards and Calibration	437
6.2	Basic Methods of Pressure Measurement	439

6.3	Deadweight Gages and Manometers Manometer Dynamics.	440
6.4	Elastic Transducers	455
6.5	Force-Balance and Vibrating-Cylinder Transducers	470
6.6	Dynamic Effects of Volumes and Connecting Tubing Liquid Systems, Heavily Damped, Slow-Acting. Liquid Systems, Moderately Damped, Fast-Acting. Gas Systems with Tube Volume a Small Fraction of Chamber Volume. Gas Systems with Tube Volume Comparable to Chamber Volume. The Infinite-Line Pressure Probe. Conclusion.	473
6.7	Dynamic Testing of Pressure-Measuring Systems	483
6.8	High-Pressure Measurement	489
6.9	Low-Pressure (Vacuum) Measurement McLeod Gage. Knudsen Gage. Momentum-Transfer (Viscosity) Gages. Thermal-Conductivity Gages. Ionization Gages. Dual-Gage Technique.	491
6.10	Sound Measurement Sound-Level Meter. Microphones. Pressure Response of a Capacitor Microphone. Acoustic Intensity. Acoustic Emission.	498
6.11	Pressure-Signal Multiplexing Systems	521
	Problems	524
	Bibliography	526
7	Flow Measurement	527
7.1	Local Flow Velocity, Magnitude and Direction Flow Visualization. Velocity Magnitude from Pitot-Static Tube. Velocity Direction from Yaw Tube, Pivoted Vane, and Servoed Sphere. Dynamic Wind-Vector Indicator. Hot-Wire and Hot- Film Anemometers. Hot-Film Shock-Tube Velocity Sensors. Laser Doppler Velocimeter.	527
7.2	Gross Volume Flow Rate Calibration and Standards. Constant-Area, Variable-Pressure-Drop Meters ("Obstruction" Meters). Averaging Pitot Tubes. Constant- Pressure-Drop, Variable-Area Meters (Rotameters). Turbine Meters. Positive-Displacement Meters. Metering Pumps. Electromagnetic Flowmeters. Drag-Force Flowmeters. Ultrasonic Flowmeters. Vortex-Shedding Flowmeters. Miscellaneous Topics.	566
7.3	Gross Mass Flow Rate Volume Flowmeter Plus Density Measurement. Direct Mass Flowmeters. Problems	597
	Bibliography	608
8	Temperature and Heat-Flux Measurement	612
8.1	Standards and Calibration	612
8.2	Thermal-Expansion Methods Bimetallic Thermometers. Liquid-in-Glass Thermometers. Pressure Thermometers.	619

8.3	Thermoelectric Sensors (Thermocouples) Common Thermocouples. Reference-Junction Considerations. Special Materials, Configurations, and Techniques.	625
8.4	Electrical-Resistance Sensors Conductive Sensors (Resistance Thermometers). Bulk Semiconductor Sensors (Thermistors).	642
8.5	Junction Semiconductor Sensors	652
8.6	Digital Thermometers	656
8.7	Radiation Methods Radiation Fundamentals. Radiation Detectors. Unchopped (DC) Broadband Radiation Thermometers. Chopped (AC) Broadband Radiation Thermometers. Chopped (AC) Selective-Band (Photon) Radiation Thermometers. Automatic Null-Balance Radiation Thermometers. Monochromatic-Brightness Radiation Thermometers (Optical Pyrometers). Two-Color Radiation Thermometers. Blackbody-Tipped Fiber-Optic Radiation Thermometer. Infrared Imaging Systems. Fluoroptic Temperature Measurement.	657
8.8	Temperature-Measuring Problems in Flowing Fluids Conduction Error. Radiation Error. Velocity Effects.	692
8.9	Dynamic Response of Temperature Sensors Dynamic Compensation of Temperature Sensors.	702
8.10	Heat-Flux Sensors Slug-Type Sensors. Steady-State or Asymptotic Sensors (Gardon Gage). Application Considerations.	706
	Problems	710
	Bibliography	711
9	Miscellaneous Measurements	713
9.1	Time, Frequency, and Phase-Angle Measurement	713
9.2	Liquid Level	720
9.3	Humidity	725
9.4	Chemical Composition	729
9.5	Particle Instruments and Clean-Room Technology	731
9.6	Micro-machined Silicon and Quartz Sensors	740
9.7	Fiber-Optic Sensors Problems Bibliography	743 746 747

Part 3 Manipulation, Transmission, and Recording of Data

10	Manipulating, Computing, and Compensating Devices	751
10.1	Bridge Circuits	751
10.2	Amplifiers Operational Amplifiers. Instrumentation Amplifiers. Noise	757

	Problems, Shielding, and Grounding. Chopper, Chopper-Stabilized, and Carrier Amplifiers. Charge Amplifiers and Impedance Converters. Concluding Remarks.	777
10.3	Filters	
	Low-Pass Filters. High-Pass Filters. Bandpass Filters. Band-Rejection Filters. Digital Filters. A Hydraulic Bandpass Filter for an Oceanographic Transducer. Mechanical Filters for Accelerometers. Filtering by Statistical Averaging.	
10.4	Integration and Differentiation	790
10.5	Dynamic Compensation	804
10.6	Instrument Servomechanisms	808
10.7	Addition and Subtraction	810
10.8	Multiplication and Division	813
10.9	Function Generation and Linearization	816
10.10	Amplitude Modulation and Demodulation	822
10.11	Voltage-to-Frequency and Frequency-to-Voltage Converters	823
10.12	Analog-to-Digital and Digital-to-Analog Converters; Sample/Hold Amplifiers	826
10.13	Signal and System Analyzers	834
10.14	Microprocessor Applications	837
	Problems	842
	Bibliography	843
11	Data Transmission	844
11.1	Cable Transmission of Analog Voltage and Current Signals	844
11.2	Cable Transmission of Digital Data	847
11.3	Fiber-Optic Data Transmission	850
11.4	FM/FM Radio Telemetry	851
11.5	Pneumatic Transmission	854
11.6	Synchro Position Repeater Systems	854
11.7	Slip Rings and Rotary Transformers	854
11.8	Data Storage with Delayed Playback, an alternative to Data Transmission	859
	Problems	859
	Bibliography	859
12	Voltage-Indicating and -Recording Devices	860
12.1	Standards and Calibration	860
12.2	Analog Voltmeters and Potentiometers	860
12.3	Digital Voltmeters and Multimeters	867
12.4	Electromechanical Servotype <i>XT</i> and <i>XY</i> Recorders	871
12.5	Optical Galvanometer Oscillographs	872
12.6	Fiber-Optic CRT Recording Oscilloscope	879
12.7	Thermal and Electrostatic Array Recorders	879
12.8	Cathode-Ray Oscilloscopes and Graphic Displays	880
12.9	Digital Waveform Recorders and Digital Storage Oscilloscopes	886
12.10	Digital Printers/Plotters	888

12.11	Magnetic Tape and Disk Recorders/Reproducers	890
12.12	Speech Input-Output Devices	895
	Problems	896
	Bibliography	896
13	Engineered Data Acquisition and Processing Systems	897
13.1	A Versatile, Modular System Emphasizing Analog Signal Processing	898
13.2	Compact Data Loggers	902
13.3	Instrument Interconnection Systems	909
13.4	Sensor-Based, Computerized Data Systems	911
	Bibliography	921
14	Computer-Aided Experimentation	922
14.1	Introduction	922
14.2	Functional Description of the System	922
14.3	Functional Description of the Computer System	924
14.4	Sensors	925
14.5	Overall System Configuration; Interfacing	926
14.6	Overall Plan of the Test Sequence and Computer Program	929
14.7	Algorithms for the Speed and Torque Calculation	932
14.8	Programming Details	934
	Apparatus Setup, Lines 10 to 390. Torque-Sensor Calibration, Lines 410 to 870. Speed/Torque Testing, Lines 1120 to 1480.	
14.9	Conclusion	945
	Problems	946
	Bibliography	947
	Index	949