
MODERN MEASUREMENTS

Fundamentals and Applications

Edited by

**ALESSANDRO FERRERO
DARIO PETRI
PAOLO CARBONE
MARCANTONIO CATELANI**

 **IEEE**
IEEE PRESS

WILEY

PREFACE

There are several books related to instrumentation and measurement that explain how measurement methods work and how instruments can be designed, selected, and used to implement the different measurement methods needed to obtain the desired measurement result with the desired accuracy. But no books are available, to our knowledge, that explain what “measuring” means and which essential activities must be performed to accomplish a measurement.

This is somehow surprising, because measurement has always been an important, and sometimes critical, activity that has developed with the humankind, becoming a significant part of its culture. Today everything is measured, and we are surrounded by instruments, often without being aware of their silent presence. Despite this pervasive presence of every kind of instruments and the many kinds of measurements we perform in our everyday life, measurement is probably the only relevant technical activity that is rarely grounded on a well-defined and widely known models. It is rather considered as a mere tool, not as an independent branch of science and technique, so that it is often confined to the role of appendix, sometimes not so relevant, of other subjects.

This book is aimed at filling this gap, and providing a unique framework, valid for any kind of measurement. So, do not expect too many technical details on how a specific instrument works, or a specific measurement method can be implemented. Many excellent books already cover these topics. Here you will find those fundamental bricks that are present in every modern instrument and are part of every modern measurement activity. You will also discover the importance of some “hidden” bricks, such as the primary standards, without which no universally recognized measurement would be possible.

You will discover the importance of digital signal processing in modern measurements, and how critical it may become if some specific mathematical issues are disregarded. Do not expect to find how modern oscilloscopes or multimeters are designed and developed, since this is the aim of many dedicated books and handbooks. On the contrary, you will find how the aforementioned fundamental bricks can be combined to implement two of the most popular and used instruments.

Most importantly, and maybe surprisingly for those readers who are not yet familiar with this field, you will discover that every measured value is “wrong” in the sense that, due to a number of different factors that influence any measuring activity, we are never able to know the so-called “true value” of the measurand. But you will also discover that we know how to quantify how “wrong” our measurement result is. This is achieved by providing the so-called measurement uncertainty, which tells us how good and reliable the obtained measurement result is. This information is essential when we use a measurement result as the input element of a decision-making process and we wish to quantify the risk of a wrong decision.

To accomplish our goal, we have organized this book into two parts. Part I (Fundamentals) presents a model of the modern measurement activity and the already recalled fundamental bricks. It starts (Chapter 1) with a general model that introduces these bricks and the uncertainty concept, provides an overview of these bricks in the following chapters, and finishes (Chapter 7) with a more general and complex model that encompasses both traditional (*hard*) measurements and *soft* measurements, aimed at quantifying nonphysical concepts, such as quality, satisfaction, and comfort.

Part II (Applications) is aimed at showing how the concepts presented in Part I can be usefully applied to design and implement measurements in some very important and broad fields. We cover system identification (Chapter 8), reliability (Chapter 9), and electromagnetic compatibility (EMC) (Chapter 10) not only for their importance in many application areas, from manufacturing to health and safety, but also because their intrinsic complexity is the perfect test bench to prove the usefulness of the concepts introduced in Part I.

We sincerely hope that this book may provide a new, systematic insight into such an important field as instrumentation and measurement, and can help both experts and beginners, with a useful analysis tool, to understand the essential meaning of the measuring activity, regardless of its specific application.

The Editors

CONTENTS

PREFACE	xv
ACRONYMS	xvii
I FUNDAMENTALS	1
1 MEASUREMENT MODELS AND UNCERTAINTY	3
<i>Alessandro Ferrero and Dario Petri</i>	
1.1 Introduction / 3	
1.2 Measurement and Metrology / 4	
1.3 Measurement Along the Centuries / 5	
1.3.1 Measurement in Ancient Greece / 6	
1.3.2 Measurement in the Roman Empire / 6	
1.3.3 Measurement in the Renaissance Period / 7	
1.3.4 Measurement in the Modern Age / 8	
1.3.5 Measurement Today / 9	
1.4 Measurement Model / 10	
1.4.1 A First Measurement Model / 11	
1.4.2 A More Complex Measurement Model / 16	
1.4.3 Final Remarks / 19	
1.5 Uncertainty in Measurement / 20	
1.5.1 The Origin of the Doubt / 21	

- 1.5.2 The Different Effects on the Measurement Result / 23
- 1.5.3 The Final Effect / 25
- 1.6 Uncertainty Definition and Evaluation / 27
 - 1.6.1 The Error Concept and Why it Should be Abandoned / 28
 - 1.6.2 Uncertainty Definition: The GUM Approach / 29
 - 1.6.3 Evaluating Standard Uncertainty / 31
 - 1.6.4 The Combined Standard Uncertainty / 35
- 1.7 Conclusions / 39
- Further Reading / 40
- References / 41
- Exercises / 41

2 THE SYSTEM OF UNITS AND THE MEASUREMENT STANDARDS

47

Franco Cabiati

- 2.1 Introduction / 47
- 2.2 Role of the Unit in the Measurement Process / 48
- 2.3 Ideal Structure of a Unit System / 50
- 2.4 Evolution of the Unit Definition / 52
- 2.5 The SI System of Units / 53
- 2.6 Perspectives of Future SI Evolution / 59
- 2.7 Realization of Units and Primary Standards / 62
 - 2.7.1 Meter Realization and Length Standards / 65
 - 2.7.2 Kilogram Realization and Mass Standards: Present Situation / 66
 - 2.7.3 Kilogram Realization: Future Perspective / 67
 - 2.7.4 Realization of the Second and Time Standards / 69
 - 2.7.5 Electrical Unit Realizations and Standards: Present Situation / 71
 - 2.7.6 Electrical Units Realization and Standards: Future Perspective / 76
 - 2.7.7 Kelvin Realization and Temperature Standards: Present Situation / 78
 - 2.7.8 Kelvin Realization and Temperature Standards: Future Perspective / 79
 - 2.7.9 Mole Realization: Present Situation / 80
 - 2.7.10 Mole Realization: Future Perspective / 81
 - 2.7.11 Candela Realization and Photometric Standards / 82
- 2.8 Conclusions / 83

Further Reading / 83

References / 84

Exercises / 84

3 DIGITAL SIGNAL PROCESSING IN MEASUREMENT 87

Alessandro Ferrero and Claudio Narduzzi

3.1 Introduction / 87

3.2 Sampling Theory / 88

3.2.1 Sampling and Fourier Analysis / 89

3.2.2 Band-Limited Signals / 92

3.2.3 Interpolation / 95

3.3 Measurement Algorithms for Periodic Signals / 96

3.3.1 Sampling Periodic Signals / 97

3.3.2 Estimation of the RMS Value / 99

3.4 Digital Filters / 102

3.5 Measuring Multi-Frequency Signals / 106

3.5.1 Finite-Length Sequences / 107

3.5.2 Discrete Fourier Transform / 111

3.5.3 Uniform Window / 113

3.5.4 Spectral Leakage / 114

3.5.5 Leakage Reduction by the Use of Windows / 116

3.6 Statistical Measurement Algorithms / 119

3.7 Conclusions / 120

Further Reading / 121

References / 122

Exercises / 122

4 AD AND DA CONVERSION 125

Niclas Björnsell

4.1 Introduction / 125

4.2 Sampling / 125

4.2.1 Quantization / 126

4.2.2 Sampling Theorem / 129

4.2.3 Signal Reconstruction / 130

4.2.4 Anti-Alias Filter / 133

4.3 Analog-to-Digital Converters / 133

4.3.1 Flash ADCs / 133

4.3.2 Pipelined ADCs / 134

- 4.3.3 Integrating ADCs / 134
- 4.3.4 Successive Approximation Register ADCs / 135
- 4.4 Critical ADC Parameters / 135
 - 4.4.1 Gain and Offset / 136
 - 4.4.2 Integral and Differential Non-linearity / 137
 - 4.4.3 Total Harmonic Distortion and Spurious-Free Dynamic Range / 139
 - 4.4.4 Effective Number of Bits / 139
- 4.5 Sampling Techniques / 139
 - 4.5.1 Oversampling / 139
 - 4.5.2 Sigma-Delta, $\Sigma\Delta$ / 140
 - 4.5.3 Dither / 141
 - 4.5.4 Time-Interleaved / 142
 - 4.5.5 Undersampling / 142
 - 4.5.6 Harmonic Sampling / 143
 - 4.5.7 Equivalent-Time Sampling / 143
 - 4.5.8 Model-Based Post-correction / 144
- 4.6 DAC / 144
 - 4.6.1 Binary-Weighted / 144
 - 4.6.2 Kelvin Divider / 145
 - 4.6.3 Segmented / 145
 - 4.6.4 R-2R / 145
 - 4.6.5 PWM DAC / 145
- 4.7 Conclusions / 146
- Further Reading / 146
- References / 146
- Exercises / 147

5 BASIC INSTRUMENTS: MULTIMETERS

149

Daniel Slomovitz

- 5.1 Introduction / 149
- 5.2 History / 150
- 5.3 Main Characteristics / 153
 - 5.3.1 Ranges / 153
 - 5.3.2 Number of Digits and Resolution / 155
 - 5.3.3 Accuracy / 158
 - 5.3.4 Loading Effects / 159
 - 5.3.5 Guard / 160
 - 5.3.6 Four Terminals / 161

- 5.3.7 Accessories / 162
- 5.3.8 AC Measurements / 164
- 5.3.9 Safety / 167
- 5.3.10 Calibration / 170
- 5.3.11 Selection / 171
- 5.4 Conclusions / 171
- Further Reading / 172
- References / 172
- Exercises / 173

6 BASIC INSTRUMENTS: OSCILLOSCOPES

175

Jorge Fernandez Daher

- 6.1 Introduction / 175
- 6.2 Types of Waveforms / 176
 - 6.2.1 Sinewave / 176
 - 6.2.2 Square or Rectangular Wave / 176
 - 6.2.3 Triangular or Sawtooth Wave / 176
 - 6.2.4 Pulses / 177
- 6.3 Waveform Measurements / 177
 - 6.3.1 Amplitude / 177
 - 6.3.2 Phase Shift / 177
 - 6.3.3 Period and Frequency / 177
- 6.4 Types of Oscilloscopes / 177
- 6.5 Oscilloscope Controls / 181
 - 6.5.1 Vertical Controls / 183
 - 6.5.2 Horizontal Controls / 184
 - 6.5.3 Trigger System / 185
 - 6.5.4 Display System / 187
- 6.6 Measurements / 188
 - 6.6.1 Peak-to-Peak Voltage / 188
 - 6.6.2 RMS Voltage / 188
 - 6.6.3 Rise Time / 188
 - 6.6.4 Fall Time / 188
 - 6.6.5 Pulse Width / 188
 - 6.6.6 Period / 190
 - 6.6.7 Frequency / 190
 - 6.6.8 Phase Shift Measurements / 190
 - 6.6.9 Mathematical Functions / 190

- 6.7 Performance Characteristics / 191
 - 6.7.1 Bandwidth / 191
 - 6.7.2 Rise Time / 191
 - 6.7.3 Channels / 193
 - 6.7.4 Vertical Resolution / 193
 - 6.7.5 Gain Accuracy / 193
 - 6.7.6 Horizontal Accuracy / 193
 - 6.7.7 Record Length / 193
 - 6.7.8 Update Rate / 194
 - 6.7.9 Connectivity / 195
- 6.8 Oscilloscope Probes / 195
 - 6.8.1 Passive Probes / 196
 - 6.8.2 Active Probes / 197
- 6.9 Using the Oscilloscope / 199
 - 6.9.1 Grounding / 199
 - 6.9.2 Calibration / 199
- 6.10 Conclusions / 199
- Further Reading / 200
- References / 200
- Exercises / 201

7 FUNDAMENTALS OF HARD AND SOFT MEASUREMENT

203

Luca Mari, Paolo Carbone and Dario Petri

- 7.1 Introduction / 203
- 7.2 A Characterization of Measurement / 206
 - 7.2.1 Measurement as Value Assignment / 206
 - 7.2.2 Measurement as Process Performed by a Metrological System / 209
 - 7.2.3 Measurement as Process Conveying Quantitative Information / 209
 - 7.2.4 Measurement as Morphic Mapping / 210
 - 7.2.5 Measurement as Mapping on a Given Reference Scale / 213
 - 7.2.6 Measurement as Process Conveying Objective and Inter-Subjective Information / 215
 - 7.2.7 The Operative Structure of Measurement / 216
 - 7.2.8 A Possible Definition of "Measurement" / 219
 - 7.2.9 Hard Measurements and Soft Measurements / 220
 - 7.2.10 Multidimensional Properties / 222

- 7.3 A Conceptual Framework of the Structure of Measurement / 223
 - 7.3.1 Goal Setting / 225
 - 7.3.2 Modeling / 228
 - 7.3.3 Design / 241
 - 7.3.4 Execution: Setup, Data Acquisition, Information
Extraction and Reporting / 243
 - 7.3.5 Interpretation / 245
- 7.4 An Application of the Measurement Structure Framework:
Assessing Versus Measuring Research Quality / 246
 - 7.4.1 Motivations for Research Quality Measurement / 246
 - 7.4.2 Measurement Goal Definition / 247
 - 7.4.3 Modeling / 250
 - 7.4.4 Design / 252
 - 7.4.5 Execution / 254
 - 7.4.6 Interpretation / 255
- 7.5 Conclusions / 256
- Further Reading / 257
- References / 257
- Exercises / 260

II APPLICATIONS 263

8 SYSTEM IDENTIFICATION 265

Gerd Vandersteen

- 8.1 Introduction / 265
- 8.2 A First Example: The Resistive Divider / 265
- 8.3 A First Trial of Estimators / 267
- 8.4 From Trial-and-Error to a General Framework / 268
 - 8.4.1 Setting up the Estimator / 269
 - 8.4.2 Uncertainty on the Estimates / 270
 - 8.4.3 Model Validation / 271
 - 8.4.4 Extracting the Noise Model / 274
- 8.5 Practical Identification Framework for Instrumentation and
Measurements / 277
 - 8.5.1 Dynamic Linear Time-Invariant (LTI) Systems / 277
 - 8.5.2 From Linear to Nonlinear Systems / 280
 - 8.5.3 Sine Fitting / 280
 - 8.5.4 Calibration and Compensation Techniques / 282
- 8.6 Conclusions / 282

Further Reading / 283
References / 283
Exercises / 285

9 RELIABILITY MEASUREMENTS

287

Marcantonio Catelani

- 9.1 Introduction / 287
 - 9.2 Brief Remarks on the Concept of Quality / 288
 - 9.3 Reliability, Failure and Fault: Basic Concepts and Definitions / 288
 - 9.4 Reliability Theory / 292
 - 9.4.1 Reliability Models and Measures Related to Time to Failure / 292
 - 9.4.2 Life Distributions / 298
 - 9.4.3 Reliability Parameters / 300
 - 9.4.4 The Bath-Tube Curve / 302
 - 9.5 System Reliability Assessment / 303
 - 9.5.1 Series Configuration / 304
 - 9.5.2 Parallel Configuration / 305
 - 9.5.3 k -out-of- n Configuration / 307
 - 9.6 Analysis Techniques for Dependability / 310
 - 9.6.1 Failure Modes and Effect Analysis / 311
 - 9.6.2 Fault Tree Analysis / 312
 - 9.7 Conclusions / 313
- Further Reading / 314
References / 314
Exercises / 315

10 EMC MEASUREMENTS

317

Carlo Carobbi

- 10.1 Introduction / 317
- 10.2 Definitions and Terminology / 318
- 10.3 The Measuring Receiver / 321
 - 10.3.1 Quasi-Peak Measuring Receivers / 321
 - 10.3.2 Peak Measuring Receivers / 329
- 10.4 Conducted Emission Measurements / 329
 - 10.4.1 The Artificial Mains Network / 329
 - 10.4.2 The Current Probe / 332
- 10.5 Radiated Emission Measurements / 333
 - 10.5.1 Antennas for the 9 kHz to 30 MHz Frequency Range / 334

10.5.2 Antennas for the Frequency Range Above 30 MHz /	335
10.5.3 Measurement Sites /	339
10.6 Immunity Tests /	343
10.6.1 Conducted Immunity Tests /	343
10.6.2 Radiated Immunity Tests /	346
10.7 Conclusions /	347
Further Reading /	348
References /	348
Exercises /	351
PROBLEM SOLUTIONS	353
INDEX	371