Preface to the Fifth Edition

This book first came out in 1966; it might be useful to quickly review how it has changed (and in some ways stayed the same) over the span of some 38 years. Its original premise was that measurement science and technology was a significant field of engineering interest in its own right, rather than an adjunct to various speciality areas such as fluid mechanics or vibration. Thus, it warranted its own courses and labs that emphasized this general viewpoint. This does not mean that speciality courses in, say, vibration measurement or heat transfer measurement are not appropriate in a curriculum, but that preceding such courses (or at least at *some* point), students should encounter measurement as a basic method for studying and solving engineering problems of all types. The background needed to appreciate this generalist view has two major components: the hardware and software of measurement systems, and the methodology of experimental analysis. *Measurement Systems* has focused on the first of these, and in 1995,1 addressed the second in a new text.[1] This viewpoint continues in this fifth edition.

In 1966 personal computers were still far in the future, but mainframe machines used in a "batch mode" were already having major impacts on engineering and engineering education. As computer technology became more and more pervasive, the text recognized this trend and gradually added those computer-related topics that were relevant to the measurement process. These included computer simulation of measurement-system dynamic response, convenient statistical software, and the *vital role played by sensors in computer-aided machines and processes.* This latter application area is today a major justification for the general view of measurement espoused above. Almost every machine and process being designed today by engineers uses some form of feedback control implemented by digital hardware and software. *Every* such system includes one or more sensors that are absolutely vital to proper system functioning. A designer who has not been exposed to the "generalist" view of measurement and thus made aware of the devices and analysis methods available is at a distinct disadvantage in "inventing" a new process or machine. Since the needed computer technology is so powerful and cost/effective, the major roadblocks to implementing a new design concept are often not there but rather in the sensors and actuators. While this text is certainly not a controls book, the use of simple control concepts was always included because *feedback-control systems use sensors* and *many sensors use feedback principles* (hot-wire anemometers, servo accelerometers, chilled-mirror hygrometers, etc.). Since the book does not

[1] E. O. Doebelin, *Engineering Experimentation: Planning, Execution, Reporting,* McGraw-Hill, New York, 1995.

presume a previous course on control, these applications are presented so they are understandable to such readers. It is perhaps surprising to some that a good understanding of such dynamic systems can be achieved by simple descriptions augmented by powerful and easy-to-use simulation software. In the current edition, major use of MATLAB/SIMULINK simulation provides this effective learning tool. From the 1966 beginnings, the text devoted considerable space to the *system-dynamics viewpoint* of measurement system-dynamic response. This was originally influenced by the author's teaching of system-dynamics courses at various levels and the writing of several texts focused on this area.[2] (The 1972 text was revised and expanded in 1998.[3]) When a system-dynamics course is included early in the curriculum, this general background can then be applied and reinforced in later application courses such as control, vibration, measurement systems, vehicle dynamics, acoustics, etc. This auricular design is efficient and effective since the basic system dynamics need be presented only once, while the later application courses can penetrate more deeply into their speciality focus, while at the same time reinforcing student understanding of earlier material. While I believe that required system-dynamics courses serve this valuable function, some readers of *Measurement Systems* will certainly not have this preparation. Thus, this and earlier editions provide the needed background material in condensed, but effective, form. The current edition continues the heavy emphasis on *frequency-spectrum methods,* utilizing MATLAB (e.g., FFT) software wherever applicable.

The original organization into three major parts is retained in this new edition:

1. General concepts
2. Measuring devices
3. Manipulation, transmission, and recording of data

Within this framework, the Table of Contents gives a more detailed breakdown, which is useful in selecting the parts of the text that might be appropriate for a particular course and instructor. While the length of the text may at first seem daunting to a prospective user (instructor or student), it is not difficult to browse the content and pick out a coherent set of topics that suits the needs of a specific course. We face a similar situation at Ohio State where this text is used in three courses, two required and one elective. The first required course has a 4-hour lab and 3 hours of separate lecture for a total of 5 credit hours for one-quarter. The lecture component is perhaps stronger than in a typical measurement course because we have chosen to include a "minicourse" in applied statistics and considerable material on technical communication (written and oral). These two topics are taught from my *Engineering Experimentation* text, which has a detailed coverage. The statistics material is intended for *general* applicability, not just for measurement situations, since statistics is not taught elsewhere in the curriculum. Requiring two textbooks *(Measurement Systems* and *Engineering Experimentation)* for a single course seems prohibitively expensive, but the same two texts are also used in a required "project lab" course that follows on the heels of this course so the total expense is not unreasonable. The third course, which uses only *Measurement Systems,* is an elective for seniors and graduate students, and extends in breadth and depth from the first required course. If *Measurement Systems* seems to be too lengthy for a single course, consider that most students after graduation will likely encounter the need for this kind of information either for the design of computer-aided systems, which always require sensors and associated signal processing, or for experimental design/ development projects. If they have become familiar with the

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[2] E. O. Doebelin, "System Dynamics: Modeling and Response," Merrill, Columbus, OH, 1972; "System Modeling and Response: Theoretical and Experimental Approaches," Wiley, New York, 1980.

[3] E. O. Doebelin, "System Dynamics: Modeling, Analysis, Simulation, Design," Marcel Dekker, New York, 1998.

text by using parts of it in a course, it will become a valuable resource for their engineering practice, a feature not shared by texts that are less comprehensive.

An important part of many measurement systems is the data-acquisition and -processing software, usually implemented in a personal computer (desktop or laptop). When the previous edition was being written (late 1980s), personal computers were just arriving on the scene, and data-acquisition software for them was not widely available. Chapter 14 of that fourth edition was a brief presentation of a personal computer/software system (MACSYM) that had been designed, built, and marketed by Analog Devices specifically for data-acquisition and control applications, an unserved niche market that the company hoped to capitalize on. We acquired several of these systems for student and research use, and at that time, they met this need very well. Unfortunately for Analog Devices (which was highly successful, and continues to be with other product lines), personal computers shortly became a mass market with plummeting prices, making the MACSYM system, while technically excellent, economically unviable. Since then, many software products for personal computer data acquisition and control have appeared and today compete in this important field. Certainly the best known and most widely used is LABVIEW from National Instruments, and many engineering educators use this product for teaching/research, especially since the company offers very good educational discounts. It is not possible for a single individual to comprehensively exercise and then evaluate all the software of this class that is available, so judgments as to suitability for undergraduate teaching purposes are likely to be colored by personal experience and preferences. Based on my own surveys and hands-on experience with students in our labs, I have concluded that the DASYLAB software offers significant advantages for both teaching and many industrial applications. Perhaps National Instruments also recognized this potential since they recently bought the German software company that produces DASYLAB.

Chapter 13 of this edition is devoted to an introduction to DASYLAB, and a version of the software is provided with each copy of the book. This version does, of course, *not* allow its use with actual sensors, but one of the useful features of all DASYLAB versions is a *simulation* mode of operation, where one can easily and quickly build the entire software portion of the data-acquisition system and try it out with simulated sensor signals of any desired kind. Thus, we can develop and "debug" the software before connecting the external sensors, amplifiers, etc. This feature also makes DASYLAB an unsurpassed *teaching tool* since each student can quickly try out any ideas for a particular application before committing to specific measurement hardware for the system. I have found the learning process for DASYLAB to be *much* quicker than for LAB VIEW so you do not have to commit an entire course to learning the system; it can be easily integrated into any existing measurement lab. Also, while LABVIEW is sometimes used in a "black box" mode (where the instructor or graduate students do the programming and undergraduate students just use the resulting system to gather data), with DASYLAB, even sophisticated systems can be put together by undergraduate students themselves with just a few hours of exposure. In Chapter 13, I have tried to make this initial experience even quicker, easier, and more illuminating for the reader. I have heard from industry contacts that many companies are also finding DASYLAB to be very cost / effective, even for rather complex applications. I believe that LABVIEW is often used by applications programmers who *do nothing else,* that is, they spend *all their time* developing sophisticated software for some complex measurement/control system or for automating some commercial instrument (like a rheometer). Each rheometer sold then includes this same software; thus, the programming cost (time and money) is amortized over many instruments. When one is using the same (LABVIEW) software over and over, one can justify a long learning curve, and since it is used daily, we *do not forget* how to use it. Also, LABVIEW'S versatility allows it to deal with situations that might frustrate a less comprehensive software package. Of course, as is usual with

any class of software, this versatility comes at the price of complexity. Most mechanical engineers, however, are nor programming specialists, but rather they need to develop a data-acquisition system *occasionally,* on a "one-shot" basis, which means that the learning curve has to be short and the recall after having not used the software for a few months must be quick. I believe DASYLAB meets this sort of need in an optimum way. I hope you will at least try it to reach your own judgment.

Details of the text's topical coverage can be quickly surveyed from the Table of Contents. Also, I have taken pains to develop a very comprehensive *index,* so try that when looking for a specific item. For users of previous editions, it might be useful to here mention some of the more significant changes (such as Chapter 13 just discussed) found in the new edition. Chapter 14 also is new; there, I decided to *focus on a particular industry* and show how measurement systems apply. Of the many possibilities, I chose integrated circuit and MEMS manufacturing. These depend heavily on micro- and nanotechnology, which use:

Scanning probe microscopes
Partial-pressure analyzers for vacuum systems
Micromotion measurement and control
Contaminant particle measurement systems and clean rooms
Magnetic-levitation conveyers

to manufacture microcircuits and microscale sensors and actuators. Each of these listed topic areas is examined in some detail, and the contributions of measurement technology identified. [MEMS-type sensors (pressure transducers, accelerometers, infrared imagers, mass flow sensors, etc.) are also discussed elsewhere in the text where appropriate.]

In addition to Chapters 13 and 14, there are a number of significant changes and additions in the fifth edition, plus many minor ones too numerous to list here. The more significant changes include:

1. The material on *calibration* and *uncertainty calculations* has been thoroughly updated to reflect the latest positions of ISO and NIST.
2. Simulation examples have been updated to replace the obsolete CSMP with MATLAB/SIMULINK, and the use of *apparatus simulation* as an aid to sensor selection has been added.
3. *Sensor fusion* ("complementary filtering") with examples from aircraft altitude and attitude sensing is covered, as is the use *of observers* for the measurement of inaccessible variables.
4. Footnotes on reference material and hardware manufacturers have been augmented with *Internet* addresses.
5. The relation between *calibration accuracy* and *installed accuracy* is explained.
6. The use of *overlap graphs* to decide whether an experiment verifies or contradicts a theory is explained.
7. The effect of measurement-system errors on *quality-control decisions* is covered.
8. *MINITAB statistics software* is used wherever it is applicable and illuminating.
9. *Multiple regression* in computer-aided calibration and measurement is covered.
10. The concept of a *noise floor* caused by intrinsic random fluctuations in all physical variables is discussed.
11. Classical frequency response graphs of amplitude ratio and phase angle are augmented with *time-delay graphs,* which makes judgment of accurate frequency range much easier.
12. *Magneto resistance* and *Hall effect* motion sensors are discussed.
13. The treatment of *capacitance motion sensors* has been expanded.
14. The use of *motion-control systems* for positioning sensors or other components has been added.

15. The use of *high-speed film* and *video cameras* for motion study has been expanded.
16. Velocity sensing using *tachometer encoders, lasers,* and *microwave* (“radar”) methods has been added.
17. The treatment of “nonclassical” gyros such as the *GyroChip and fiber-optic* types, has been expanded.
18. The use of the *Global Positioning System* in measurement applications has been added.
19. Detailed *strength-of-materials* analysis of a load cell, augmented with a *finite-element* study and experimental verification, is included.
20. Methods for measuring *pressure distribution,* using Fuji pressure film, photoluminescent paint, and “crossbar” type electrical piezoresistance sensor arrays are covered.
21. Addition of *particle-image-velocimetry* (PIV) for fluid flow analysis is covered.
22. The treatment of orifice flowmetering for *compressible flow* has been revised.
23. Flow measurement with *turbine flowmeters* has been updated and revised.
24. A conceptual error in the basic *thermocouple principle* has been corrected.
25. Thermal radiation *detectors* are covered in more detail, and *uncooled microbolometer imaging systems* have been added.
26. The material on *heat flux sensors* has been updated.
27. The design example on *analog electrical differentiation* has been thoroughly revised.
28. *Digital offline dynamic compensation* using MATLAB FFT methods has been added.
29. Galvanometers used in *optical oscillographs* has been eliminated, but the use of galvanometers in motion-control systems, such as *laser scanners,* has been added.
30. A discussion of the popular *sigma-delta analog/digital converters* has been added.
31. The radio telemetry section has been thoroughly revised, and more current wireless technologies, such as *Bluetooth,* have been added.
32. A new section on *instrument connectivity* has been added.
33. The section on *strip-chart, x /y,* and *galvanometer recorders* has been revised.
34. The concept of *virtual instruments* is now included.
35. A section on *electrical current and power* measurement has been added.

A final comment on changes must be made on the subject of *solutions manuals.* This is my eleventh engineering textbook, and for the first ten, I consistently declined to produce a solutions manual. This peculiarity is not due to laziness on my part but relates rather to some “philosophical” positions that I, rightly or wrongly, hold dear. (I will not here burden you with these but have always been happy to discuss them with anyone who would listen.) My various publishers have always explained, and I agreed, that the lack of a solutions manual will surely lose some adoptions. For the present book, the publisher made clear that this time *there would be* a solutions manual, whether I, or someone else, did it. Faced with this situation, I decided that if there was to be a solutions manual, I wanted it to be a good one and thus determined to do it myself. No graduate or other students were used, and I personally produced “camera ready” copy, including all equations and illustrations. I hope it will be found useful, but since it is my first endeavor along these lines, I will welcome any comments or criticisms.

By judicious selection of topics, the two texts, *Measurement Systems* and *Engineering Experimentation,* can be used effectively, singly or together, in a wide variety of contexts. For a freshman course that introduces students to engineering and uses a hands-on lab, perhaps including “reverse engineering” of some device, to demonstrate the two major solution paths (theory and experimentation) for engineering problems, *Engineering Experimentation* could supply many useful reading assignments. These include

an easily understandable and practically useful introduction to statistical viewpoints and methods, the role of experimentation in design and development, and guidance for written and oral communication. Later in the curriculum, we often find labs tied to some theory course or stand-alone labs that come after certain theory courses have been completed. When a lab is focused on a specific area such as, say, vibration, *Measurement Systems* can supply the needed background on the pertinent sensors, signal conditioning, and data acquisition and -processing software. Such use, of course, only employs a fraction of the material available in the text, so the expense becomes an issue. There may or may not exist a suitable measurement text devoted only to vibration, but this book will likely be just as expensive. If a curriculum has a number of such specialty labs, *Measurement Systems* will likely have the material needed in all of them. In such a case, one would hope that textbook requirements would be coordinated so that students would purchase only one text for use in all these labs. If statistical methods, experiment design, and technical communication are included in some or all of these labs, the cost of *Engineering Experimentation* might be "amortized" over the several courses. If, as at Ohio State, you find it difficult to "squeeze in" a statistics course taught in your mathematics or statistics department, the "minicourse" provided by *Engineering Experimentation* can be embedded in one or more labs and may provide a practical viewpoint often lacking in mathematics department presentations.

Many curricula now include one or more "capstone" courses that emphasize design and give students practice in applying the specialty courses encountered earlier in their studies. At Ohio State, we have traditionally had two such required senior courses, one focused on design and another devoted to experimental methods. At present, we are trying out another approach, which uses a sequence of courses/labs that allow students to design, build, and experimentally test a machine or process. These projects are often suggested by industrial sponsors who interact with the students and instructors to provide an experience more typical of actual engineering practice. These sponsors provide some equipment or apparatus, and lend some financial support. For courses devoted specifically to experimentation or for sequences that include it as an important component, *Engineering Experimentation,* possibly augmented by *Measurement Systems,* can provide useful content.

As mentioned earlier, I believe the optimum organization is to provide, somewhere in the curriculum, a *general* measurement lab/course where the science and technology of measurement is presented as an important engineering field in its own right. For such a course, *Measurement Systems* could be a good choice, perhaps augmented by *Engineering Experimentation,* depending on the course's intended focus and coverage. Even for such a course, it will be necessary, due to the breadth and depth of the book, to carefully select the student assignments, but this is actually made *easier* because there is so much to choose from that most needs can be satisfied. If, as at Ohio State, there is a more advanced measurement-systems course (probably elective, for seniors and/or graduate students), then *Measurement Systems* will again provide the needed material for a wide variety of needs. For this advanced course, I have over the years developed some homework problems and projects that, due to their length, were not included in any of my books but rather were provided in a locally printed manual. In teaching this course, in addition to weekly homework assignments (some from *Measurement Systems,* some from the manual), I assign a "project" that runs for most of the quarter. The manual provides extensive background notes in addition to the requested student homework. Three such projects currently are in the manual:

1. Preliminary design of a viscosimeter
2. Vibration isolation methods for sensitive instruments and machines
3. Design of a vibrating-cylinder ultra-precision pressure transducer

Some of the "weekly" homework problems in the manual are in the following areas:

1. Theory and simulation study of a carrier-amplifier system
2. Accelerometer selection for a drop-test shock machine
3. Dynamic compensation for a thermocouple
4. Use of the correlation function in pipeline leak detection
5. Sensor fusion ("complementary filtering")
6. Frequency-modulated (FM) sensors and digital integration
7. FFT methods for sensor dynamic compensation
8. Use of FFT analysis to document pressure transducer dynamics based on shock tube testing

If any instructor wants a copy of this manual or a "Xeroxable" master for printing copies for students, please contact me at 614-882-2670 to make arrangements to get the material, "at cost." I do not have an electronic copy.