Types of Applications of Measurement Instrumentation

1.1 WHY STUDY MEASUREMENT SYSTEMS?

The study of any subject matter in engineering should be motivated by an appreciation of the uses to which the material might be put in the everyday practice of the profession. Measurement systems are used for many detailed purposes in a wide variety of application areas. Our approach will be to start with some specific applications in a specific industry and then generalize this picture by developing classification schemes that apply to all possible situations.

While measurement is used in many contexts, I want to introduce some basic ideas using the automotive industry as an example. This industry employs measurement in many ways and is thus a good choice for exploring the various uses of measurement tools. In the text title, the term “measurement system” is meant to include all components in a chain of hardware and software that leads from the measured variable to processed data. Let us start examining the use of measurement in the automotive industry “at the beginning,” that is, with the conceptual design process, where a new automobile or truck is first conceived and the basic configuration developed. Because a modern automobile uses as many as 40 or 50 sensors (measuring devices) in implementing various functions necessary to the operation of the car, an automobile designer must be aware of the instruments available for the various measurements and how they operate and interface with other parts of the system. As new sensors are invented, designers must keep up with such developments since they may allow improvements in car design and operation. Lack of such sensor-knowledge can severely restrict the range of designs that one can conceive, thus limiting improvements in overall car performance. While sensor specialists will at later stages of design consider the measuring devices in great detail, the conceptual designer must have a basic appreciation of their capabilities, so that the initial design does not neglect any useful possibilities.
Once the conceptual stage of design is well underway, measurement system considerations arise in new contexts. Many engineered products are nowadays designed using the methods of concurrent engineering where design and manufacturing are integrated, rather than being considered sequentially, as was often the case in earlier times. Before concurrent engineering became common, design was generally completed first, manufacturing considerations addressed only later, and costly revisions and delays (or poor designs) were often the result. With concurrent engineering, product design concepts are not “frozen” until both function and manufacturability have been reconciled. That is, the design and manufacturing engineers work in coordinated teams, blending their expertise right from the beginning of the design process. Both functionality and manufacturability considerations often require the design process to include laboratory testing of one kind or another. For example, if a new material is being considered, we may need to run strength tests to develop data needed by the design engineers. Or, a new or revised manufacturing process may require statistical response surface experiments to find the effects of process variables on performance and/or cost. Finally, availability from suppliers of new components, such as improved shock absorbers, may require performance testing to decide whether their use is warranted in the new design. We see that laboratory testing and the associated measurement systems are thus a vital part of the design process.

As design and development proceed, prototype subsystems and finally entire vehicles will be produced. These are used as “test beds” to evaluate performance and then feed back information to the design/manufacturing teams. That is, initial designs usually have unsuspected flaws, which are revealed by building and testing the prototypes. Also, “pencil and paper” or computer-aided designs always are based on theories that are never exactly correct, so experimental testing is needed to verify, or improve, theoretical calculations. We begin to appreciate that design relies heavily on experimental testing at every stage of the process.

We have seen that experimentation is often needed during the design phase to help in the development of the manufacturing processes for the product. Once the design has been finalized, then manufacture of the product in quantity, rather than the “one of a kind” mode used during development, can commence. When we examine actual production machinery and processes, we often find that these manufacturing tools are controlled by a so-called feedback mechanism. In such a scheme, some quality parameter of the part produced is measured with appropriate sensors. This measured value is compared with a desired value of the parameter, and if the desired and measured values do not agree within some allowable tolerance, a controller adjusts the machine or process until the product is “on specification.” Perhaps the most obvious example of this general situation is the machining of parts to specific dimensions. Here the measuring devices are precision gages that measure shaft diameters, hole sizes, lengths, etc. Robots used to weld, spray paint, or assemble parts are also usually feedback devices that use motion and force sensors.

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to control the robots' operation. Again it is clear that measurement plays a significant role in almost every manufacturing enterprise.

Turning now to the final product, a modern automobile, as mentioned earlier, relies on a multitude of sensors for its optimum operation. Some of these play essentially a "monitoring" role, that is, they measure and display to the driver, information useful for safe and efficient operation of the car. Speedometers tell us the vehicle's speed, while tachometers display engine RPM. Fuel gages keep track of the gas supply, and temperature sensors warn of overheating. Recent developments include use of the Global Positioning System (based on satellites) to locate the car on an electronic map and guide the driver to a desired destination. Many other sensors are part of feedback controls that optimize engine operation by measuring such variables as atmospheric pressure, air f low rate, fuel/air ratio, engine temperatures, etc. Acceleration sensors (accelerometers) measure vehicle motion during a crash and signal air bags to deploy if the crash is sufficiently severe. Brake-cylinder pressure and wheel-speed sensors control the antilock braking system to give better driver control on slippery surfaces. To keep costs down, many automotive sensors use micro-electro-mechanical systems (MEMS). Using manufacturing techniques borrowed from integrated-circuit technology, miniature sensors are mass produced at low cost from materials such as silicon. A recent example is the GyroChip, a replacement for the classical gyroscopic instrument used to measure angular velocity. This sensor is being used in cars to augment vehicle stability during severe or emergency maneuvers.

1.2 CLASSIFICATION OF TYPES OF MEASUREMENT APPLICATIONS

I used the automotive industry as a familiar example to introduce you to the varied applications of measurement in engineering. To help you organize your thinking on this subject I now want to generalize the topic of measurement applications. Fortunately, all the specific examples I gave from the auto industry, and in fact, examples from any industry, can be classified into only three major categories:

1. Monitoring of processes and operations.
2. Control of processes and operations.
3. Experimental engineering analysis.

That is, I suggest that every application of measurement, including those not yet "invented," can be put into one of the three groups just listed or some combination of them. Let us now explore this scheme of classification in general terms and also relate it to our earlier automotive examples.

Monitoring of processes and operations refers to situations where the measuring device is being used to keep track of some quantity. The thermometers, barometers, radars, and anemometers used by the weather bureau fit this definition. They simply indicate the condition of the environment, and their readings do not serve any control functions in the ordinary sense. Similarly, water, gas, and electric
meters in the home keep track of the quantity of the commodity used so that the cost to the user can be computed. In our automotive illustration, the speedometer, fuel gage, outdoor temperature sensor, and compass would belong to this monitoring class of applications.

Control\(^2\) of processes and operations is one of the most important classes of measurement application. This usually refers to an automatic feedback control system, as diagramed in generic terms in Fig. 1.1. This type of application is sufficiently important that most undergraduate curricula in mechanical, aerospace, electrical, chemical, and industrial engineering will include a required course (and several electives) in control systems.

The subject of feedback control is pertinent to this text on measurement systems in two basic ways, one of which is the use of sensors in feedback control systems, as just mentioned. The other relates to the fact that many measurement systems themselves use feedback principles in their operation. One could in fact say that sensors are used in feedback systems and feedback systems are used in sensors. Of the many possible examples of the latter, we mention the hot-wire anemometer, a device for measuring rapidly varying fluid velocity. Without feedback, the hot wire used in the instrument is accurate only for velocity fluctuations of frequency less than about 100 Hz. By redesigning the instrument to use feedback, this limit is extended to about 30,000 Hz, making the instrument much more useful.

The operation of systems such as that of Fig. 1.1 is briefly described as follows: We want to control some “process,” such as the heating of our house; to be specific, we want to keep the temperature near some desired value, such as 70° F. The process is influenced by various “disturbances” (such as the outdoor temperature) that we can not control and also by an input of energy and/or material that we are able to manipulate, using some “final control element” (the gas valve in our furnace). The design principle of all feedback control systems says that we should

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measure the variable which we want to control, compare it (in a “controller”) with its desired value, and then, based on the “error” between the two, manipulate the final control element in such a way as to drive the controlled variable closer to its desired value. We see that this basic design concept means that every feedback control system will have at least one measuring device as a vital component. Since feedback systems are used in literally millions of applications for controlling temperature, pressure, shaft speed, fluid flow, robot arm position, aircraft speed and altitude, etc., these control applications are one of the most important uses of measurement systems.

Returning to our earlier automotive examples, feedback control applications are found in the car’s speed control system, the antilock braking system, the coolant temperature regulating system, the air-conditioning system, the engine pollution controls, and many more. Also, the majority of the manufacturing tools and processes used to produce the car are under feedback control.

This text is not one on feedback control; however, when feedback is used in the measurement system itself, we will not avoid discussion of its implications. Fortunately, this can usually be done without requiring that the reader have taken a controls course or be expert in this technology.

Experimental engineering analysis is that part of engineering design, development, and research that relies on laboratory testing of one kind or another to answer questions. That is, as engineers, we have only two basic ways of solving engineering problems: theory and experimentation. Some (usually simple) problems can be adequately solved using theory alone. Most problems require a judiciously selected blend of theory and experiment. It is not unusual for the “lab testing” portion of an engineering project to consume more than half of the total resources. As a result, most engineers need to be proficient in planning and conducting this phase of the effort. The text just referenced addresses the entire process; the current text concentrates on that portion intimately related to the measurement system itself.

Since the choice of how much theory and how much experiment to use in a particular application is difficult and important, we want to provide some guidelines to help organize your thinking, at least in a general way. Figures 1.2 and 1.3 compare and contrast the features of these two problem-solving methods. If we decide to use experimentation, it is helpful to realize that all engineering experiments can be put into a relatively small number of classes. This classification can be accomplished in several ways, but one which I have found meaningful is given in Fig. 1.4.

1.3 COMPUTER-AIDED MACHINES AND PROCESSES

In constructing useful machines and processes for society, it is now extremely common for engineers to include in the design, as dedicated components of an overall system, computers of various sizes. Inexpensive, compact, and powerful computer hardware and software can make possible significant advances in productivity,

### PART 1 General Concepts

| 1. | Often give results that are of general use rather than for restricted application. |
| 2. | Invariably require the application of simplifying assumptions. Thus, not the actual physical system but rather a simplified “mathematical model” of the system is studied. This means the theoretically predicted behavior is always different from the real behavior. |
| 3. | In some cases, may lead to complicated mathematical problems. This has blocked theoretical treatment of many problems in the past. Today, increasing availability of high-speed computing machines allows theoretical treatment of many problems that could not be so treated in the past. |
| 4. | Require only pencil, paper, computing machines, etc. Extensive laboratory facilities are not required. (Some computers are very complex and expensive, but they can be used for solving all kinds of problems. Much laboratory equipment, on the other hand, is special-purpose and suited only to a limited variety of tasks.) |
| 5. | No time delay engendered in building models, assembling and checking instrumentation, and gathering data. |

| Figure 1.2 Features of theoretical methods. |

| 1. | Often give results that apply only to the specific system being tested. However, techniques such as dimensional analysis may allow some generalization. |
| 2. | No simplifying assumptions necessary if tests are run on an actual system. The true behavior of the system is revealed. |
| 3. | Accurate measurements necessary to give a true picture. This may require expensive and complicated equipment. The characteristics of all the measuring and recording equipment must be thoroughly understood. |
| 4. | Actual system or a scale model required. If a scale model is used, similarity of all significant features must be preserved. |
| 5. | Considerable time required for design, construction, and debugging of apparatus. |

| Figure 1.3 Features of experimental methods. |

Product quality, efficiency, flexibility, and safety. While the nontechnical public often (wrongly) views the entire system as a “computer,” it is important that we not encourage this misconception. The computer is helpless to control any machine or process without the sensors that measure critical process variables or the actuators...
CHAPTER 1 Types of Applications of Measurement Instrumentation

1. Testing the validity of theoretical predictions based on simplifying assumptions; improvement of theory, based on measured behavior.
   Example: frequency-response testing of mechanical linkage for resonant frequencies.

2. Formulation of generalized empirical relationships in situations where no adequate theory exists.
   Example: determination of friction factor for turbulent pipe flow.

3. Determination of material, component, and system parameters, variables, and performance indices.
   Example: determination of yield point of a certain alloy steel, speed-torque curves for an electric motor, thermal efficiency of a steam turbine.

4. Study of phenomena with hopes of developing a theory.
   Example: electron microscopy of metal fatigue cracks.

5. Solution of mathematical equations by means of analogies
   Example: solution of shaft torsion problems by measurements on soap bubbles.

Figure 1.4 Types of experimental-analysis problems.

("final control elements") that manipulate process inputs and thus affect the process controlled variables. Thus, many of the amazing feats of engineering accomplished by computer-aided devices depend heavily on the availability and proper operation of associated measurement systems.

1.4 CONCLUSION

Whatever the nature of the application, intelligent selection and use of measurement instrumentation depend on a broad knowledge of what is available and how the performance of the equipment may be best described in terms of the job to be done. New equipment is continuously being developed, but certain basic devices have proved their usefulness in broad areas and undoubtedly will be widely used for many years. A representative cross section of such devices is discussed in this text. These devices are of great interest in themselves; they also serve as the vehicle for the presentation and development of general techniques and principles needed in handling problems in measurement instrumentation. In addition, these general concepts are useful in treating any devices that may be developed in the future.

The treatment is also intended to be on a level that will be of service to not only the user, but also the designer of measurement instrumentation equipment. There are two main reasons for this emphasis. First, much experimental equipment (including measurement instruments) is often "homemade," especially in smaller companies where the high cost of specialized gear cannot always be justified. Second, the instrument industry is a large and growing one which utilizes many engineers in
a design capacity. While the general techniques of mechanical and electrical design, as applied to machines are also applicable to instruments, in many cases a rather different point of view is necessary in instrument design. This is due, in part, to the fact that the design of machines is mainly concerned with considerations of power and efficiency, whereas instrument design almost completely neglects these areas and concerns itself with the acquisition and manipulation of information. Since a considerable number of engineering graduates will work in the instrument industry, their education should include treatment of the most significant aspects of this area.

The third class of applications listed earlier, experimental engineering analysis, requires not only familiarity with measurement systems, but also some understanding of the planning, execution, and evaluation of experiments. While all these aspects of experimental work might be treated in a single text or course, I have chosen in the present text to concentrate on a thorough exposition of the measurement system itself. A comprehensive treatment of the overall problems and methods of engineering experimentation is presented in any companion text. There, a major emphasis is on statistical methods, especially some simplified and practical approaches to statistical design of experiments. The two books together give a complete and in-depth coverage of all aspects of engineering experimental work.

PROBLEMS

1.1 By consulting various technical journals in the library, find accounts of experimental studies carried out by engineers or scientists. Find three such articles, reference them completely, explain briefly what was accomplished, and attempt to classify them according to one or more categories of Fig. 1.4.

1.2 Give three specific examples of measuring-instrument applications in each of the following areas: (a) monitoring of processes and operations, (b) control of processes and operations, (c) experimental engineering analysis.

1.3 Compare and contrast the experimental and the theoretical approaches to the following problems:

(a) What is the tolerable vibration level to which astronauts may safely be exposed in launch vehicles?

(b) Find the relationship between applied force \( F \) and resulting friction torque \( T_f \) in the simple brake of Fig. P1.1.

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(c) Find the location of the center of mass of the rocket shown in Fig. P1.2 if the shapes, sizes, and materials of all the component parts are known.

Figure P1.2

(d) At what angle with the horizontal should a projectile be launched to achieve the greatest horizontal range?

BIBLIOGRAPHY

Books
PART 1 General Concepts


Periodicals
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5. Journal of Instrument Society of America
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