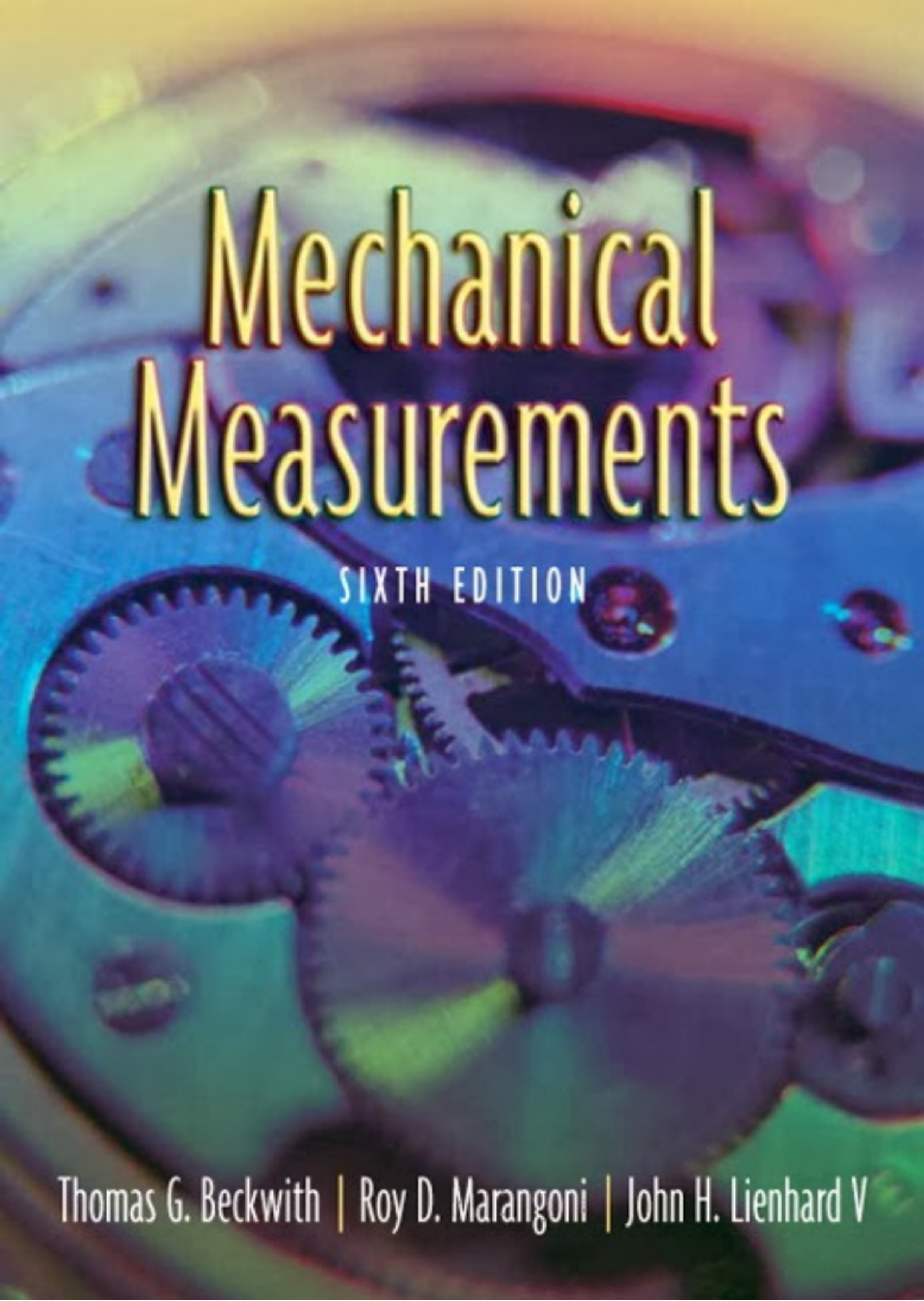

Mechanical Measurements

SIXTH EDITION

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Mechanical Measurements

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The Process of Measurement: An Overview

1 INTRODUCTION

It has been said, "Whatever exists, exists in some amount." The determination of the amount is what measurement is all about. If those things that exist are related to the practice of mechanical engineering, then the determination of their amounts constitutes the subject of *mechanical measurements*.[1]

The process or the act of measurement consists of obtaining a quantitative comparison between a predefined *standard* and a *measurand*. The word *measurand* is used to designate the particular physical parameter being observed and quantified; that is, the input quantity to the measuring process. The act of measurement produces a *result* (see Fig. 1).

The standard of comparison must be of the same character as the measurand, and usually, but not always, is prescribed and defined by a legal or recognized agency or organization—for example, the National Institute of Standards and Technology (NIST), formerly called the National Bureau of Standards (NBS), the International Organization for Standardization (ISO), or the American National Standards Institute (ANSI). The meter, for example, is a clearly defined standard of length.

Such quantities as temperature, strain, and the parameters associated with fluid flow, acoustics, and motion, in addition to the fundamental quantities of mass, length, time, and so on, are typical of those within the scope of mechanical measurements. Unavoidably,

[1] *Mechanical measurements* are not necessarily accomplished by mechanical means: rather, it is to the measured quantity itself that the term *mechanical* is directed. The phrase *measurement of mechanical quantities*, or *of parameters*, would perhaps express more completely the meaning intended. In the interest of brevity, however, the subject is simply called *mechanical measurements*.

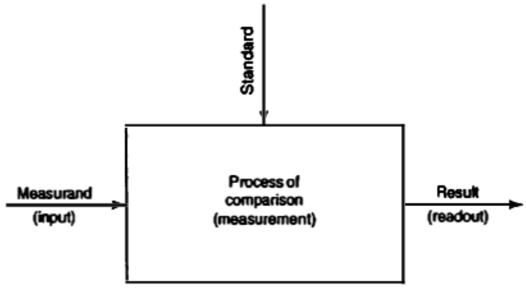

FIGURE 1: Fundamental measuring process.

the measurement of mechanical quantities also involves consideration of things electrical, since it is often convenient or necessary to change, or *transduce*, a mechanical measurand into a corresponding electrical quantity.

2 THE SIGNIFICANCE OF MECHANICAL MEASUREMENT

Measurement provides quantitative information on the actual state of physical variables and processes that otherwise could only be estimated. As such, measurement is both the vehicle for new understanding of the physical world and the ultimate test of any theory or design. Measurement is the fundamental basis for all research, design, and development, and its role is prominent in many engineering activities.

All mechanical design of any complexity involves three elements: experience, the rational element, and the experimental element. The element of experience is based on previous exposure to similar systems and on an engineer's common sense. The rational element relies on quantitative engineering principles, the laws of physics, and so on. The experimental element is based on measurement—that is, on measurement of the various quantities pertaining to the operation and performance of the device or process being developed. Measurement provides a comparison between what was intended and what was actually achieved.

Measurement is also a fundamental element of any control process. The concept of control *requires* the measured discrepancy between the actual and the desired performances. The controlling portion of the system must know the magnitude and direction of the difference in order to react intelligently.

In addition, many daily operations require measurement for proper performance. An example is in the central power station. Temperatures, flows, pressures, and vibrational amplitudes must be constantly monitored by measurement to ensure proper performance of the system. Moreover, measurement is vital to commerce. Costs are established on the basis of *amounts* of materials, power, expenditure of time and labor, and other constraints.

To be useful, measurement must be reliable. Having incorrect information is potentially more damaging than having no information. The situation, of course, raises the question of the accuracy or *uncertainty* of a measurement. Arnold O. Beckman, founder of Beckman Instruments, once stated, "One thing you learn in science is that there is no *perfect* answer, no *perfect* measure."[2] It is quite important that engineers interpreting the results of measurement have some basis for evaluating the likely uncertainty. Engineers should *never* simply read a scale or printout and blindly accept the numbers. They must carefully place realistic tolerances on each of the measured values, and not only should have a doubting mind but also should attempt to quantify their doubts. We will discuss uncertainty in more detail in Section 8.

3 FUNDAMENTAL METHODS OF MEASUREMENT

There are two basic methods of measurement: (1) *direct comparison* with either a primary or a secondary standard and (2) *indirect comparison* through the use of a calibrated system.

3.1 Direct Comparison

How would you measure the length of a bar of steel? If you were to be satisfied with a measurement to within, let us say, $\frac{1}{8}$ in. (approximately 3 mm), you would probably use a steel tape measure. You would compare the length of the bar with a *standard* and would find that the bar is so many inches long because that many inch-units on your standard are the same length as the bar. Thus you would have determined the length by *direct comparison*. The standard that you have used is called a secondary standard. No doubt you could trace its ancestry back through no more than four generations to the primary length standard, which is related to the speed of light.

Although to measure by direct comparison is to strip the measurement process to its barest essentials, the method is not always adequate. The human senses are not equipped to make direct comparisons of all quantities with equal facility. In many cases they are not sensitive enough. We can make direct comparisons of small distances using a steel rule, with a precision of about 1 mm (approximately 0.04 in.). Often we require greater accuracy. Then we must call for additional assistance from some more complex form of measuring system. Measurement by direct comparison is thus less common than is measurement by *indirect comparison*.

3.2 Using a Calibrated System

Indirect comparison makes use of some form of transducing device coupled to a chain of connecting apparatus, which we shall call, in toto, the *measuring system*. This chain of devices converts the basic form of input into an analogous form, which it then processes and presents at the output as a known function of the original input. Such a conversion is often necessary so that the desired information will be intelligible. The human senses are simply not designed to detect the strain in a machine member, for instance. Assistance is required from a system that senses, converts, and finally presents an analogous output in the form of a displacement on a scale or chart or as a digital readout.

Processing of the analogous signal may take many forms. Often it is necessary to increase an amplitude or a power through some form of amplification. Or in another case it may be necessary to extract the desired information from a mass of extraneous input by a process of filtering. A remote reading or recording may be needed, such as ground recording of a temperature or pressure within a rocket in flight. In this case the pressure or

[2] Emphasis added by the authors.

temperature measurement must be combined with a radio-frequency signal for transmission to the ground.

In each of the various cases requiring amplification, or filtering, or remote recording, electrical methods suggest themselves. In fact, the majority of transducers in use, *particularly for dynamic mechanical measurements*, convert the mechanical input into an analogous electrical form for processing.

4 THE GENERALIZED MEASURING SYSTEM

Most measuring systems fall within the framework of a general arrangement consisting of three phases or stages:

Stage 1. A detection-transduction, or *sensor-transducer*, stage
Stage 2. An intermediate stage, which we shall call the *signal-conditioning* stage
Stage 3. A terminating, or *readout-recording*, stage

Each stage consists of a distinct component or group of components that performs required and definite steps in the measurement. These are called *basic elements*; their scope is determined by their function rather than by their construction. Figure 2 and Table 1 outline the significance of each of these stages.

4.1 First, or Sensor-Transducer, Stage

The primary function of the first stage is to detect or to sense the measurand. At the same time, ideally, this stage should be insensitive to every other possible input. For instance, if it is a pressure pickup, it should be insensitive to, say, acceleration; if it is a strain gage, it should be insensitive to temperature; if a linear accelerometer, it should be insensitive to angular acceleration; and so on. Unfortunately, it is rare indeed to find a detecting device that is completely selective. Unwanted sensitivity is a measuring error, called *noise* when it varies rapidly and *drift* when it varies very slowly.

Frequently one finds more than a single transduction (change in signal character) in the first stage, particularly if the first-stage output is electrical.

4.2 Second, or Signal-Conditioning, Stage

The purpose of the second stage of the general system is to modify the transduced information so that it is acceptable to the third, or terminating, stage. In addition, it may perform one or more basic operations, such as selective filtering to remove noise, integration, dif-

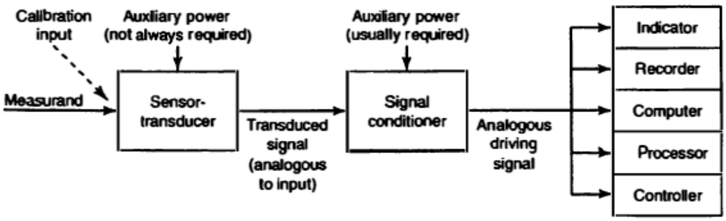

FIGURE 2: Block diagram of the generalized measuring system.

TABLE 1: Stages of the General Measurement System

Stage 1: Sensor-Transducer	Stage 2: Signal Conditioning	Stage 3: Readout-Recording
Senses desired input to exclusion of all others and provides analogous output	Modifies transduced signal into form usable by final stage. Usually increases amplitude and/or power, depending on requirement. May also selectively filter unwanted components or convert signal into pulsed form	Provides an indication or recording in form that can be evaluated by an unaided human sense or by a controller. Records data digitally on a computer
Types and Examples *Mechanical*: Contacting spindle, spring-mass, elastic devices (e.g., Bourdon tube for pressure, proving ring for force), gyro	*Types and Examples* *Mechanical*: Gearing, cranks, slides, connecting links, cams, etc.	*Types and Examples* *Indicators (displacement type)*: Moving pointer and scale, moving scale and index, light beam and scale, electron beam and scale (oscilloscope), liquid column
Hydraulic-pneumatic: Buoyant float, orifice, venturi, vane, propeller	*Hydraulic-pneumatic*: Piping, valving, dashpots, plenum chambers	*Indicators (digital type)*: Direct alphanumeric readout
Optical: Photographic film, photoelectric diodes and transistors, photomultiplier tubes, holographic plates	*Optical*: Mirrors, lenses, optical filters, optical fibers, spatial filters (pinhole, slit)	*Recorders*: Digital printing, inked pen and chart, direct photography, magnetic recording (hard disk)
Electrical: Contacts, resistance, capacitance, inductance, piezoelectric crystals and polymers, thermocouple, semiconductor junction	*Electrical*: Amplifying or attenuating systems, bridges, filters, telemetering systems, various special-purpose integrated-circuit devices	*Processors and computers*: Various types of computing systems, either special-purpose or general, used to feed readout/recording devices and/or controlling systems
		Controllers: All types

ferentiation, or telemetering, as may be required.

Probably the most common function of the second stage is to increase either amplitude or power of the signal, or both, to the level required to drive the final terminating device. In addition, the second stage must be designed for proper matching characteristics between the first and second and between the second and third stages.

4.3 Third, or Readout-Recording, Stage

The third stage provides the information sought in a form comprehensible to one of the human senses or to a controller. If the output is intended for immediate human recognition, it is, with rare exception, presented in one of the following forms:

1. As a *relative displacement*, such as movement of an indicating hand or displacement of oscilloscope trace