Course Notes 1: Introduction to Biomedical Instrumentation

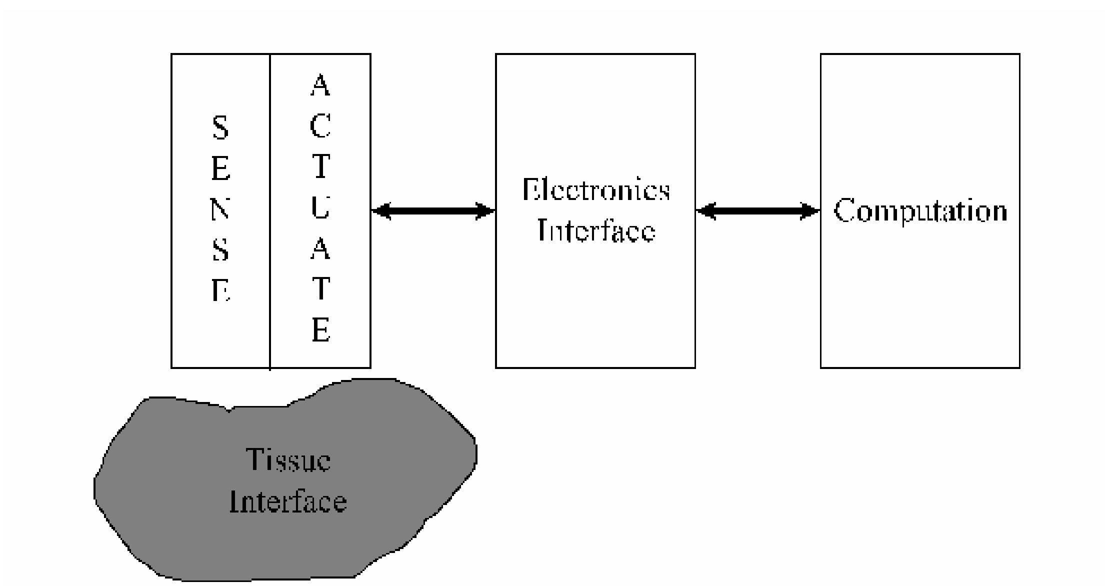
1 Section Objectives

- Understand the canonical structure of biomedical instrumentation systems.
- Learn the qualitative functions of the four primary system components (sensors, actuators, electronics interface, computation unit)
- Learn the technical vocabulary associated with instrumentation and design and basic signal analysis (italicized words and phrases).
- Learn / review the static and dynamic performance characteristics for instrumentation systems.

2 Introduction to Biomedical Instruments

"Biomedical instruments" refer to a very broad class of devices and systems. A biomedical instrument is an ECG machine to many people. To others, it's a chemical biosensor, and to some it's a medical imaging system. Current estimates place the worldwide market for biomedical instruments at over $200 billion. Biomedical instruments are ubiquitous; they are significant to the broader technology and biotechnology sectors; and, finally, they are vital to many medical and scientific fields. Bottom line: This course is worthwhile!!

Even though there is a wide variety of instruments, almost all of them can be modeled using the simple diagram below.



Basic model of instrumentation systems.

All biomedical instruments must interface with biological materials (by definition). The interface can by direct contact or by indirect contact (e.g., induced fields).

In this course we will primarily study sensing systems, which means that the system front-end will generally be a sensing element. Other than this restriction, we will cover all aspects of typical biomedical instrumentation systems. We will do them in the following order:

1. **Basic Sensors and Principles** -- including biopotential electrodes
2. **Electronic Interfacing**: including system noise figure, system bandwidth, pre-amplifiers, post-amps, instrumentation amps, A/D and D/A converters, aliasing, triggering and signal averaging
3. **Computation**: including data capture and signal processing
4. **Systems**: complete system response using specific examples (electromyogram, pressure sensors and blood pressure measurements, flow sensors and blood flow measurements, and chemical biosensors)

2.1 Sensors and Actuators

A sensor must:

- detect biochemical, bioelectrical, or biophysical parameters
- reproduce the physiologic time response of these parameters
- provide a safe interface with biological materials

An actuator must:

- deliver external agents via direct or indirect contact
- control biochemical, bioelectrical, or biophysical parameters
- provide a safe interface with biologic materials

2.2 Electronics Interface

The electronics interface must:

- match the electrical characteristics of the sensor/actuator with the computation unit
- preserve signal-to-noise ratio (SNR) of sensor
- preserve efficiency of actuator
- preserve bandwidth (i.e., time response) of sensor/actuator
- provide a safe interface with the sensor/actuator
- provide a safe interface with the computation unit
- provide secondary signal processing functions for the system

2.3 Computation Unit

The computation unit must:

- provide primary user interface
- provide primary control for the overall system

- provide data storage for the system
- provide primary signal processing functions for the system
- maintain safe operation of the overall system

2.4 Types of Biomedical Instrumentation Systems

Types of Biomedical Instrumentation Systems

- Direct / Indirect
- Invasive / Noninvasive
- Contact / Remote
- Sense / Actuate
- Dynamic / Static

Direct/Indirect: The sensing system measure a physiologic parameter directly, such as the average volume blood flow in an artery, or measures a parameter **related to** the physiologic parameter of interest (e.g., ECG recording at the body surface is related to propagation of the action potential in the heart but is **not a** measurement of the propagation waveform).

Invasive/Noninvasive: Direct electrical recording of the action potential in nerve fibers using an implantable electrode system is an example of an invasive sensor. An imaging system measuring blood flow dynamics in an artery (e.g., ultrasound color flow imaging of the carotid artery) is an example of a non-invasive sensor.

Contact/Remote: A strain gauge sensor attached to a muscle fiber can record deformations and forces in the muscle. An MRI or ultrasound imaging system can measure internal deformations and forces without contacting the tissue.

Sense/Actuate: A sensor detects biochemical, bioelectrical, or biophysical parameters. An actuator delivers external agents via direct or indirect contact and/or controls biochemical, bioelectrical, or biophysical parameters. An automated insulin delivery pump is an example of a direct, contact actuator. Noninvasive surgery with high intensity, focused ultrasound (HIFU) is an example of a remote, noninvasive actuator.

Dynamic/Static: Static instruments measure temporal averages of physiologic parameters. Real-time instruments have a time response faster than or equal to the physiologic time constants of the sensed parameter. For example a real-time, ultrasound Doppler system can measure changes in arterial blood velocity over a cardiac cycle.

Passive Instruments, Active Instruments, and Balancing Instruments.

2.5 Medical Measurement Parameters

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2.6 Characteristics of Signals

"A signal is any physical quantity that varies with time (or other independent variable) and carries information. Signals can be classified as either continuous or discrete. A continuous signal changes smoothly, without interruption. A discrete signal changes in definite steps, or in a quantized manner. The terms *continuous* and *discrete* can be applied either to the value (amplitude) or to the time characteristics of a signal"

In nature (including biology), most signals are *analog*, i.e., they take on continuous values (amplitude and time) within a particular range.

"*Continuous-time*" signals exist continually at all times (during a specified time period).

"*Discrete-time*" signals are defined only at selected instances of time.

Sampling is the process to convert continuous-time signals to discrete-time signals. Quantizing is the process that converts continuous (in amplitude) discrete-time signals to digital signals.

Signals in which time is the independent variable are referred to as "*time-domain*" signals. Likewise, when frequency is the independent variable, the signals are referred to as "*frequency-domain*" signals.

3 General Instrument Performance Parameters

3.1 Systematic and Random Error

Systematic errors are errors that consistently occur in a measurement in the same direction. The common sources of systematic errors are inaccurate calibration, mismatched impedances, response-time error, nonlinearities, equipment malfunction, environmental change, and loading effects. Systematic errors are often unknown to the user. The best way to detect systematic errors are to repeat the measurement with a completely different technique using different instruments.

Random errors tend to vary in both directions from the true value randomly (or stochasticly). With properly designed instruments, random errors are generally small relative to the *measurand* (the physical signal to be measured). Common sources of random error include electrical noise, interference, vibration, gain variation of amplifiers, leakage currents, drift, observational error, motion artifact (for contact sensors), random interfering inputs, etc.

3.2 Static Performance Parameters

Static characteristics describe the performance for dc or very low frequency inputs. The properties of the output for a wide range of constant inputs demonstrate the quality of the measurement.

Accuracy

The accuracy of a single measured quantity is the difference between the true value and the measured value divided by the true value:

$$Accuracy = \frac{True\ value - measured\ value}{True\ value}$$

Accuracy is often quoted as a percentage. Many times, the true value is unknown over all operating conditions, so the true value is approximated with some standard.

Precision
The precision of a measurement expresses the number of distinguishable alternatives from which a given result is selected. On most modern instrumentation systems the precision is ultimately determined by the analog-to-digital converter *(AID)* characteristics.

Resolution
The smallest quantity that can be measured with certainty is the resolution. Resolution expresses the degree to which nearly equal values of a quantity can be discriminated.

Reproducibility
The ability of an instrument to give the same output for equal inputs applied over some period of time is called reproducibility. Drift is the primary limit on reproducibility.

Sensitivity
Sensitivity describes changes in system output for a given change in a single input. It is quantified by holding all inputs constant except one. This one input is varied incrementally over the normal operating range, producing a range of outputs needed to compute the sensitivity.

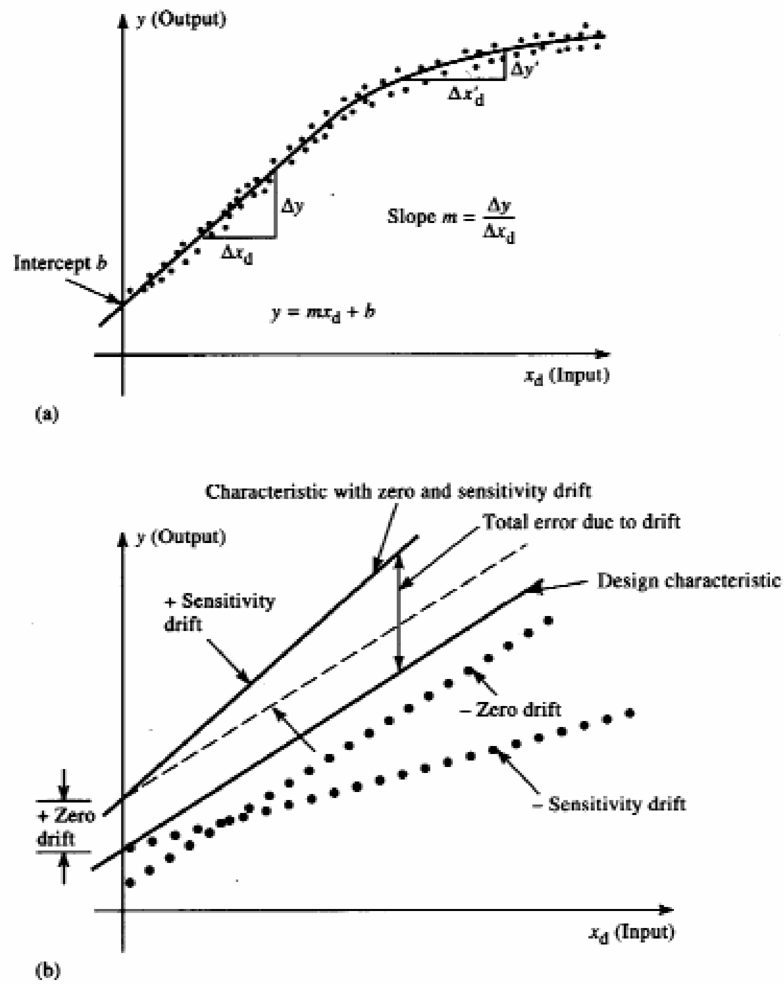

Figure 1.3 (a) Static-sensitivity curve that relates desired input x_d to output y. Static sensitivity may be constant for only a limited range of inputs. (b) Static sensitivity: zero drift and sensitivity drift. Dotted lines indicate that zero drift and sensitivity drift can be negative. [Part (b) modified from *Measurement Systems: Application and Design,* by E. O. Doebelin. Copyright © 1990 by McGraw-Hill, Inc. Used with permission of McGraw-Hill Book Co.]

Zero (Offset) Drift
Offset drift is one parameter determining reproducibility. It is measured by monitoring the system output with no change in input. Any changes that occur are simply result of system offset.

Sensitivity Drift
Sensitivity drift is the second primary contributor to irreproducibility. It causes error proportional to the magnitude of the input. These drift parameters are summarized in a typical sensor sensitivity curve below.

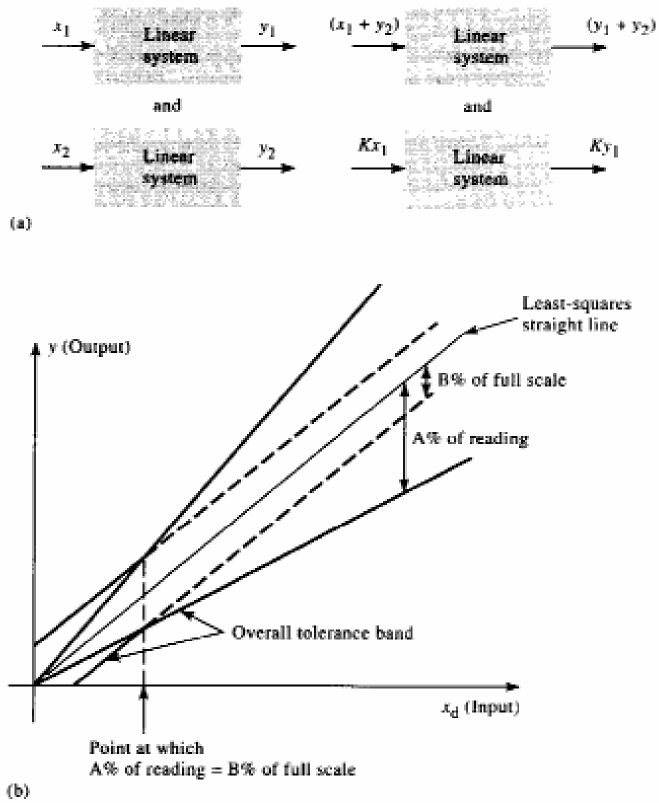

Figure 1.4 (a) Basic definition of linearity for a system or element. The same linear system or element is shown four times for different inputs. (b) A graphical illustrataion of independent nonlinearity equals ±A% of the reading, or ±B% of full scale, whichever is greater (that is, whichever permits the larger error). [Part (b) modified from *Measurement Systems: Application and Design*, by E. O. Doebelin. Copyright © 1990 by McGraw-Hill, Inc. Used with permission of McGraw-Hill Book Co.]

Linearity

A linear system satisfies the condition:

If

$$x_1 \rightarrow y_1$$
$$x_2 \rightarrow y_2$$

then the system is linear if and only if:

$$ax_1 + bx_2 \rightarrow ay_1 + by_2$$

This is the simple expression of the superposition principle for a linear system. There are many ways to express deviations from linearity for a practical system. For dynamic systems, multitone tests are often used, where the magnitude of beat frequencies between the individual tone frequencies can quantify the level of nonlinearity. For static systems, independent nonlinearity measures as shown below are often used

Dynamic Range

The dynamic range defines the ratio between the maximum undistorted signal (i.e., maximum input signal satisfying the linearity specification for the sensor) and the minimum detectable signal for a given set of operating conditions. Often the dynamic range is quoted on a logarithmic scale (i.e., dB scale).

Input Impedance

The instantaneous rate at which energy is transferred by a system (i.e., the power) is proportional to the product of an *effort* variable (e.g., voltage, pressure, force) with a *flow* variable (current, flow, velocity). The generalized impedance, ***Z***, is the ratio of the phasor equivalent of the steady-state sinusoidal effort variable to the phasor equivalent of the steady-state flow variable:

$$\tilde{Z} = \frac{\tilde{V}}{\tilde{I}}$$

where the tilde denotes phasor variables (i.e., magnitude and phase—a complex number). The phase is related to the response lag of the system to a sinusoidal input more about this for dynamic systems.

3.3 General Dynamic Performance Parameters

Dynamic characteristics require a full differential equation description of system performance. Complete system characteristics are usually approximated by the sum of static and dynamic characteristics.

Most biomedical instruments must process signals that change with time. The dynamics of the measurement system, therefore, must be chosen to properly reproduce the dynamics of the physiologic variables the system is sensing. In this course we will only consider linear, time invariant systems unless otherwise explicitly noted. For such systems, the dynamics can be fully described by simple differential equations of the form:

$$a_n \frac{d^n y(t)}{dt^n} + \ldots + a_1 \frac{dy(t)}{dt} + a_0 y(t) = b_m \frac{d^m x(t)}{dt^m} + \ldots + b_1 \frac{dx(t)}{dt} + b_0 x(t)$$

where *x(t)* is the input signal (usually the physiologic parameter of interest), *y(t)* is the output signal (usually the electronic signal), and the *a* and *b* coefficients are constants determined by the physical characteristics of the sensor system. Most practical sensor front-ends are described by differential equations of zero, first or second order (i.e., *n=0,1,2*), and derivatives of the input are usually absent, so *m=0*.

Linear, time-invariant systems are characterized by their response to sinusoidal inputs of the form $x(t) = A\sin(\omega t)$, where the output, *y(t)*, is a sinusoidal signal of the same frequency, i.e., $y(t) = B(\omega)\sin(\omega t + \phi(\omega))$. This simple characteristic is captured in the *system transfer function*, defined as a function of angular frequency $\omega = 2\pi f$:

$$\tilde{H}(\omega) = \frac{\tilde{Y}(\omega)}{\tilde{X}(\omega)} = \frac{b_m (j\omega)^m + \ldots + b_1 (j\omega) + b_0}{a_n (j\omega)^n + \ldots + a_1 (j\omega) + a_0}$$

where $j = \sqrt{-1}$ j and $\tilde{H}(\omega)$ is written in complex notation, where the magnitude of $\tilde{H}(\omega)$ equals the ratio $\tilde{B}(\omega) / \tilde{A}(\omega)$ and the phase of $\tilde{H}(\omega)$ represents the physical phase lag $\phi(\omega)$. Using the transfer function notation, the dynamic response of simple zero-, first-, and second-order systems are briefly outlined below.

Zero-Order System

A linear potentiometer can be used to measure displacement and represents a simple example of a zero order system. The differential equation describing its operation is

$$a_0 y(t) = b_0 x(t)$$

and the transfer function is

$$\tilde{H}(\omega) = \frac{\tilde{Y}(\omega)}{\tilde{X}(\omega)} = \frac{b_0}{a_0} = K$$

Note that there is no phase lag between output and input at ALL frequencies. This means the step response is instantaneous, as illustrated below.

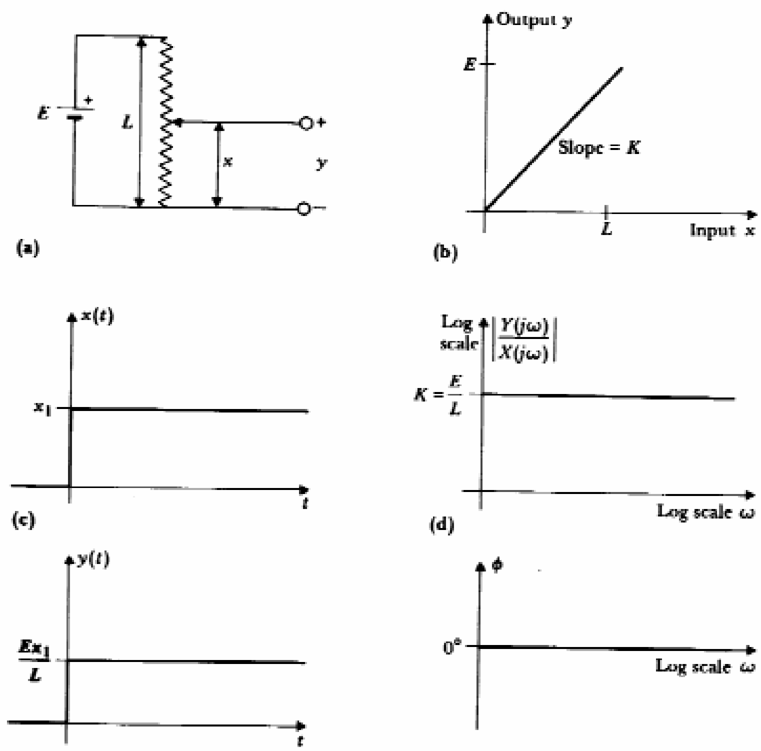

Figure 1.5 (a) A linear potentiometer, an example of a zero-order system. (b) Linear static characteristic for this system. (c) Step response is proportional to input. (d) Sinusoidal frequency response is constant with zero phase shift.

First-Order System
If the instrument contains a single energy storage element, the a first-order differential equation describes the system dynamics,

$$a_1 \frac{dy(t)}{dt} + a_0 y(t) = b_0 x(t)$$

with the associated transfer function

$$\tilde{H}(\omega) = \frac{\tilde{Y}(\omega)}{\tilde{X}(\omega)} = \frac{K}{1 + j\omega\tau}$$

where $K = b_0 / a_0$ and $\tau = a_1 / a_0$. The RC low-pass filter shown below is an example of a first order system. Note the phase lag is a function of frequency and creates a delayed step response. The system does not pass frequencies much greater than $\omega = 1/\tau$. Consequently, for a first-order sensor system there should be no significant frequency components in the physiologic input parameter greater than this cutoff frequency.

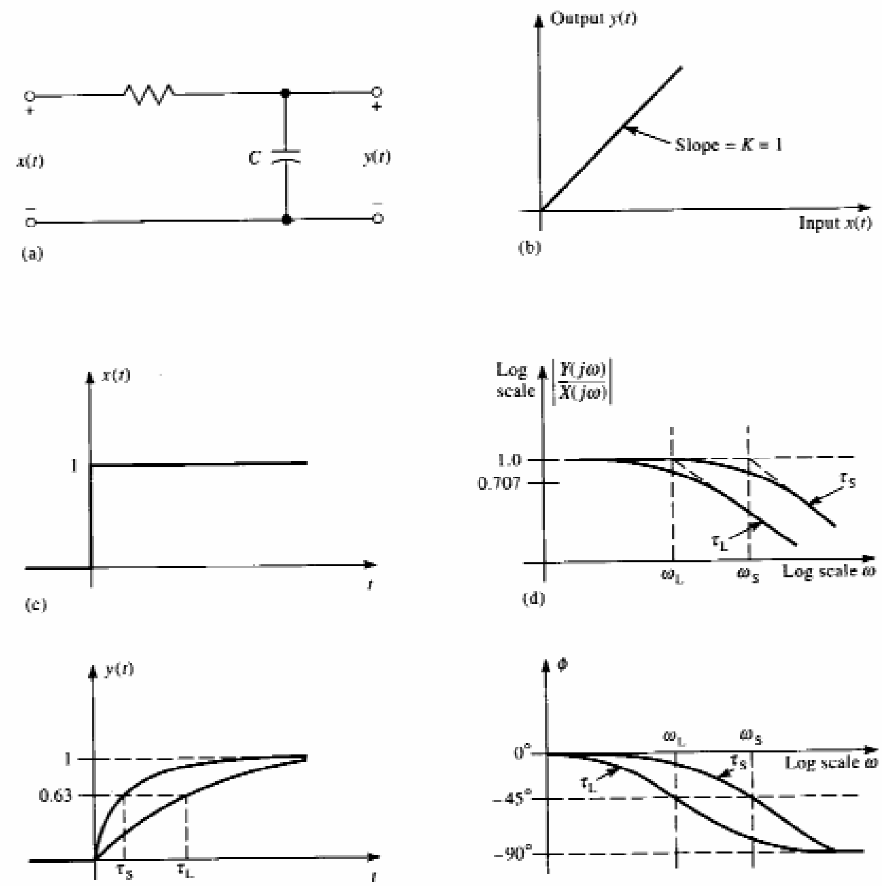

Figure 1.6 (a) A low-pass *RC* filter, an example of a first-order instrument. (b) Static sensitivity for constant inputs. (c) Step response for large time constants (τ_L) and small time constants (τ_S). (d) Sinusoidal frequency response for large and small time constants.

A second order system has two levels of energy storage with dynamics described by the differential equation

$$a_2 \frac{d^2 y(t)}{dt^2} + a_1 \frac{dy(t)}{dt} + a_0 y(t) = b_0 x(t)$$

with associate transfer function:

$$\tilde{H}(\omega) = \frac{\tilde{Y}(\omega)}{\tilde{X}(\omega)} = \frac{K}{\left(j\omega / \omega_n \right)^2 + 2\xi j\omega / \omega_n + 1}$$

where the static sensitivity is $K = b_0 / a_0$, the undamped natural frequency is $\omega_n = \left(a_0 / a_2 \right)^{0.5}$ and the dimensionless damping ratio is $\xi = a_1 / 2\sqrt{a_0 a_2}$. A mechanical force-measuring system shown below illustrates the properties of a second order system. Note the step response for underdamped, critically damped, and overdamped cases. Again, significant components in the input variable must be at frequencies less than natural frequency of the second-order system. In later sections we will see how the pre-amp, post-amp, digitization system and digital signal processing system must be matched to the transfer characteristics of the sensor element.

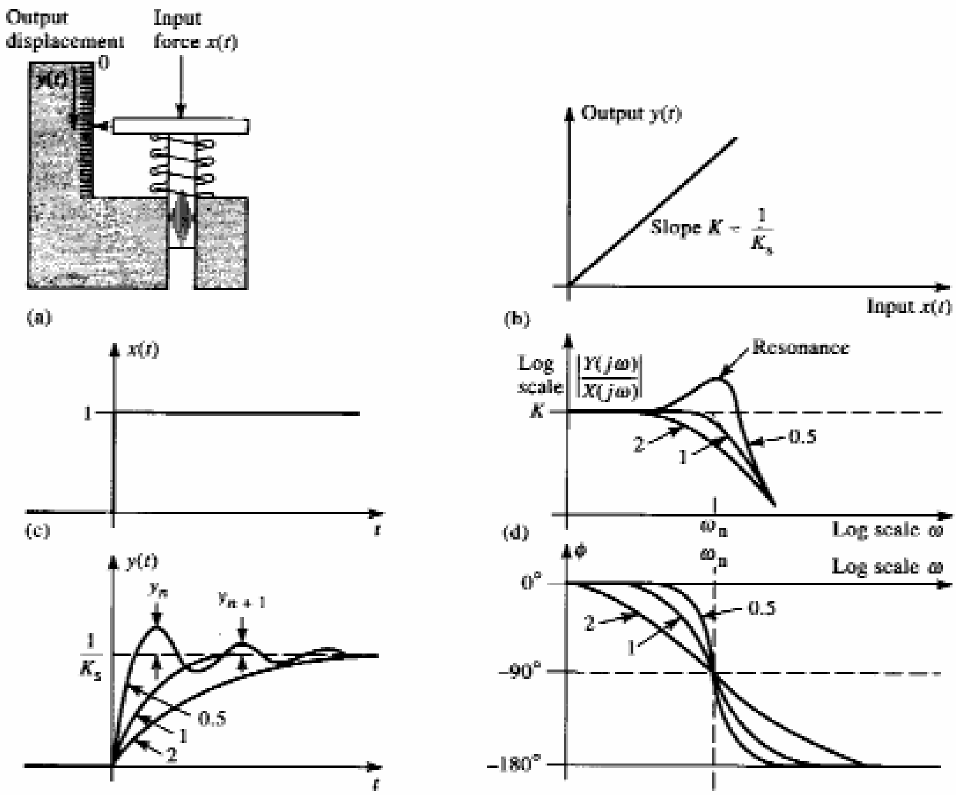

Figure 1.7 (a) Force-measuring spring scale, an example of a second-order instrument. (b) Static sensitivity. (c) Step response for overdamped case $\zeta = 2$, critically damped case $\zeta = 1$, underdamped case $\zeta = 0.5$. (d) Sinusoidal steady-state frequency response, $\zeta = 2$, $\zeta = 1$, $\zeta = 0.5$. [Part (a) modified from *Measurement Systems: Application and Design*, by E. O. Doebelin. Copyright © 1990 by McGraw-Hill, Inc. Used with permission of McGraw-Hill Book Co.]