Academic Year 94-95; semester one
Materials Engineering- Graduate Program

MEASUREMENTS ERRORS

INTRODUCTION

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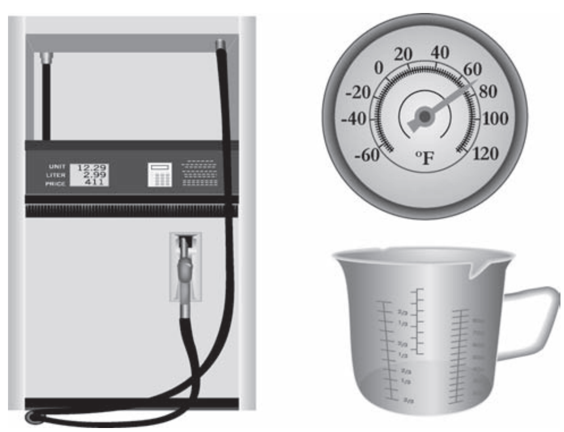
Common devices that involve measurements



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Making measurements

- Theories in physics are developed on the basis of experimental observations, or are tested by comparing predictions with the results of experiments.
- Being able to carry out experiments and understand their limitations is a critical part of physics or any experimental science.
- In every experiment you make errors; understanding what to do with these errors is required if you want to compare experiments and theories.

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What is Measurement?

- A measurement is an act of assigning a specific value to a physical variable.
- Act of measurement—the quantitative comparison between a predefined standard and a measurand to produce a measured result
- Measurand : physical parameter or variable to be measured
- Standard: basis for comparison of quantitative value to measurand.

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Standards organizations

- **ISO:** International Organization for Standardization
- **ANSI**: American National Standard Institute
- **ASTM**: American Society of Testing and Materials
- **...**

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Reliability of Measurements

- Measurements must be reliable to be useful
- Incorrect information is more damaging than no information
- There is no *perfect* measurement
- Accuracy of measurements
- Precision of measurements
- Uncertainty of measurements
- Do not accept data without questioning the source and uncertainty of the measurements

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Fundamentals Methods of Measurements

There are two basic methods of measurement:

- *Direct comparison*: with a primary or secondary standard
- *Indirect comparison*—conversion of measurand input into an analogous form which can be processed and presented as known function of input

- A transducer is required to convert the measurand into another form

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Measurement System Components

(1) sensor–transducer stage,

- to detect measurand and Convert input to a form suitable for processing e.g. : - Temp. to voltage - Force to distance

(2) signal-conditioning stage,

- to modify the transduced signal e.g. : Amplification, Attenuation, Filtering, Encoding

(3) output stage,

- to present desired output (Analog or Digital form)

(4) feedback-control stage.

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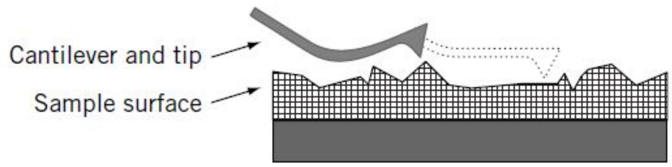
Sensors

- A physical element that employs some natural phenomenon to sense the variable being measured

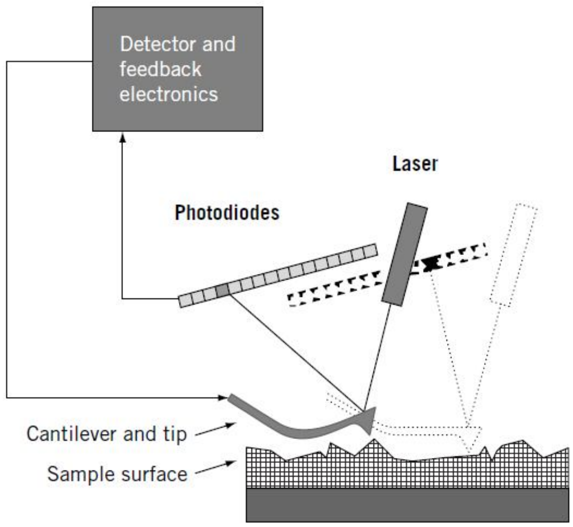


Sensor stage of an atomic-force microscope.

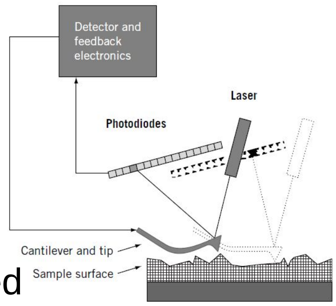
- Sensor in AFM:
  - the cantilever beam
  - the deflection under the action of a repulsive force
  - the height of the surface

➡ sensor to measure at the nanometer scale but having no means of getting an output from the sensor that we can record

Transducer



Transducer



- The laser and the light sensors (photodiodes) form the transducer component of the measurement system.
- A transducer converts the sensed information into a detectable signal.
- The signal might be mechanical, electrical, optical, or may take any other form that can be meaningfully recorded.

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Output stage

- The goal of a measurement system is to convert the sensed information into a form that can be easily quantified.
- The output stage indicates or records the value measured.
- This might be a simple readout display, a marked scale, or even a recording device such as a computer disk drive.

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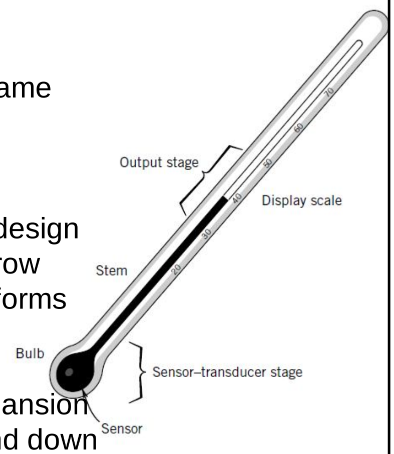
liquid-in-glass bulb thermometer

Mechanism: exchanging energy between the liquid contained within the bulb and its surroundings until the two are in thermal equilibrium. At that point they are at the same temperature.
Input signal: The energy exchange
Sensor: The liquid in the bulb
Transducer: the bulb's internal capillary design By forcing the expanding liquid into a narrow capillary, this measurement system transforms thermal information into a mechanical displacement.
Output: The phenomenon of thermal expansion of the liquid results in its movement up and down the stem, forming an output signal.
Output stage: The readout scale of the bulb thermometer serves as the output stage



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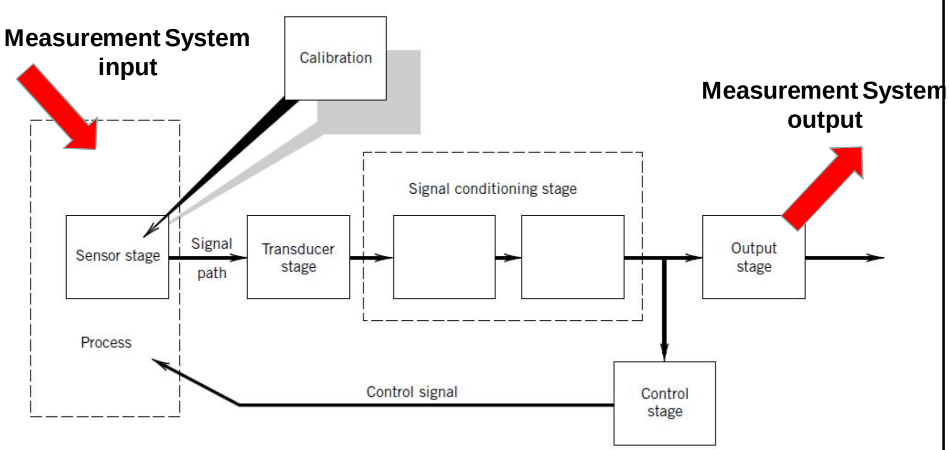
Generalized Measurement System



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(4) feedback-control stage.

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Signal-conditioning stage

- The signal-conditioning stage takes the transducer signal and modifies it to a desired magnitude.
- The optional intermediate stage
- Might be used to perform tasks such as increasing the magnitude of the signal by amplification, removing portions of the signal through some filtering technique, or providing mechanical or optical linkage between the transducer and the output stage.
- For example, the diameter of the thermometer capillary relative to the bulb volume determines how far up the stem the liquid moves with increasing temperature.
- It ‘‘conditions’’ the signal by amplifying the liquid displacement.

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Feedback-control stage

- Containing a controller that interprets the measured signal and makes a decision regarding the control of the process
- This decision results in a signal that changes the process parameter that affects the magnitude of the sensed variable
- In simple controllers, this decision is based on the magnitude of the signal of the sensed variable, usually whether it exceeds some high or low set point, a value set by the system operator.
- For example, a household furnace thermostat. The operator fixes the set point for temperature on the thermostat display, and the furnace is activated as the local temperature at the thermostat, as determined by the sensor within the device, rises or falls above or below the set point.

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Experimental Test Plan

- An experimental test serves to answer a question, so the test should be designed and executed to answer that question and that question alone.

- Designing a test to answer the question:

  ‘‘What is the fuel use of my new car?’’

- Approach: identify the variables that will be measured, but also need to look closely at other variables that will influence the result.
- Two variables to measure: distance and fuel volume consumption

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Experimental Test Plan

- What other variables might influence the results?

  - the driving route, (randomize the route by using various types of driving conditions)
  - the driver If more than one driver uses the car
  - weather and road conditions

→ the utility of the measured data is very much impacted by variables beyond the primary ones measured.
In developing the test, the proposed question to be answered will be a factor in developing the test plan

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Developing a Measurement Test Plan

- A test plan draws from the following three steps:

1. **Parameter design plan.**
   Determine the test objective and identify the process variables and parameters and a means for their control.
2. **System and tolerance design plan.**
   Select a measurement technique, equipment, and test procedure based on some preconceived tolerance limits for errors
3. **Data reduction design plan.**
   Plan how to analyze, present, and use the anticipated data.

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Variables

- Variables are entities that influence the test.
- In addition to the targeted measured variable, there may be other variables pertinent to the measured process that will affect the outcome.
- All known process variables should be evaluated for any possible cause-and effect relationships.
- **Independent Variable:** A variable that can be changed independently of other variables
- **Dependent variable:** A variable that is affected by changes in one or more other variables
- **Continuous** (such as stress under a changing load or temperature in a room) or **discrete** (such as the value of the role of dice or a test run by a single operator).

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Variables

- **Controlled variable:** it can be held at a constant value or at some prescribed condition during a measurement.
- The cause-and-effect relationship between the independent variables and the dependent variable is found by controlling the values of the independent variables while measuring the dependent variable.
- **Extraneous variables**: are not or cannot be controlled during measurement but that affect the value of the variable measured are called.
  - Their influence can confuse the clear relation between cause and effect in a measurement.
  - Can introduce differences in repeated measurements of the same measured variable taken under seemingly identical operating conditions.
  - They can also impose a false trend onto the behavior of that variable.

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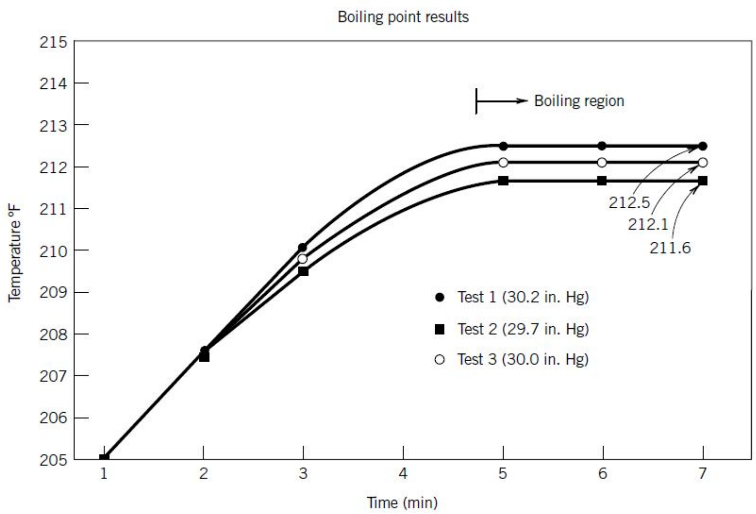
Boiling point test results for water



the local barometric pressure was not controlled (i.e., it was not held fixed between the tests), the pressure acted as an extraneous variable adding to the differences in outcomes between the test runs.

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Parameters

- As a functional grouping of variables (a moment of inertia or a Reynolds number has its value determined from the values of a grouping of variables)
- **Control parameter**: A parameter that has an effect on the behavior of the measured variable
- Available methods for establishing control parameters based on known process variables include **similarity and dimensional analysis** techniques and **physical laws**
- A parameter is controlled if its value can be maintained during a set of measurements.
- As an example, the flow rate, Q, developed by a fan depends on rotational speed, n, and the diameter, d, of the fan.

$$C_1 = Q/nd^3$$

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Noise and Interference

- **Noise** is a random variation of the value of the measured signal as a consequence of the variation of the extraneous variables
- Noise increases data scatter.
- **Interference** imposes undesirable deterministic trends on the measured value.
- Any uncontrolled influence that causes the signal or test outcome to behave in a manner different from its true behavior is interference.
- A common interference in electrical instruments comes from an AC power source and is seen as a sinusoidal wave superimposed onto the measured signal path.
- Sometimes the interference is obvious
- If the period of the interference is longer than the period over which the measurement is made, the false trend may go unnoticed.

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Effects of Noise and interference

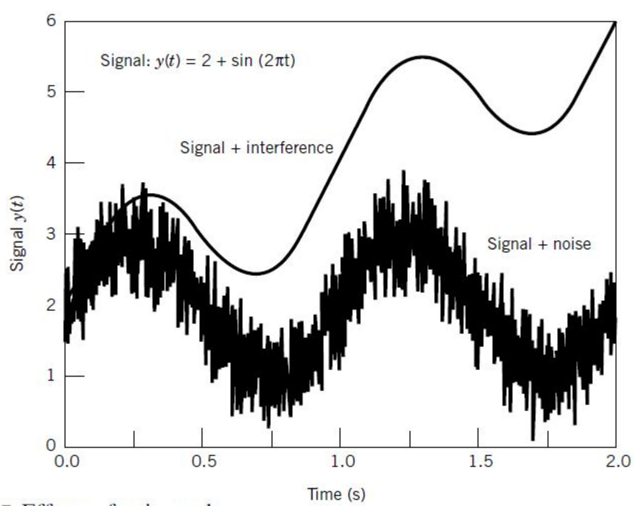

Figure 1.7 Effects of noise and interference superimposed on the signal $y(t) = 2 + \sin 2\pi t$.

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Minimizing or eliminating interference trends

- **Rondomization:** The effect of the random order on the results of the random test
  - **Random test:** a measurement matrix that sets a random order to the change in the value of the independent variable applied.
- **Repetition:** Repeated measurements made during any single test run or on a single batch.
  - Repetition helps to quantify the variation in a measured variable as it occurs during any one test or batch while the operating conditions are held under nominal control.
- **Replication:** An independent duplication of a set of measurements using similar operating conditions.
  - Replication allows for quantifying the variation in a measured variable as it occurs between different tests, each having the same nominal values of operating conditions.

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Calibration

- Applying a known input value to a measurement system for the purpose of observing the system output value
- Establishing the relationship between the input and output values
- The known value used for the calibration is called the standard
- **Static Calibration**: the values of the variables involved remain constant; that means they do not vary with time or space.
  - Only the magnitudes of the known input and the measured output are important.
  - By applying a range of known input values and by observing the system output values, a direct calibration curve can be developed for the measurement system.
  - The input value is usually a controlled independent variable, while the measured output value is the dependent variable of the calibration

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Primary Standards For Comparison and Calibration

- **SI System:** Meter – Kg -- Sec.– Kelvin – volt - Mole – Ampere – Radian
- **LENGTH (meter):** Distance traveled by light in vacuum during ***1/299792458*** of a sec.
- **MASS (Kg.):** International prototype *(alloy of platinum and iridium)* kept near Paris.
- **TIME (Sec.):** Duration of ***9192631770*** periods of the radiation emitted between two excitation levels of Cesium-133
- **TEMPERATURE (Kelvin):** $K = {}^{o}C + 273$

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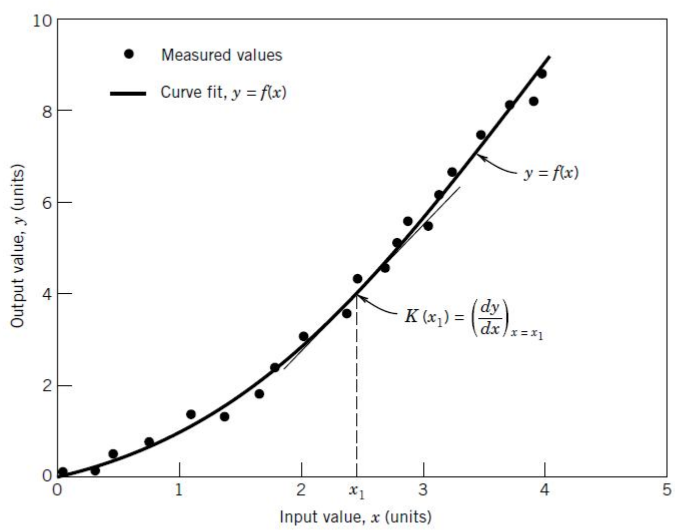
Static Calibration Curve



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Calibration

- The static calibration curve describes the static input–output relationship for a measurement system and forms the logic by which the indicated output can be interpreted during an actual measurement.
- A calibration curve can be used as part of developing a functional relationship, an equation known as a correlation, between input and output ($y=f(x)$).

- **Dynamic Calibration**: When the variables of interest are time (or space) dependent
  - a broad sense, dynamic variables are time (or space) dependent in both their magnitude and frequency content
  - A dynamic calibration determines the relationship between an input of known dynamic behavior and the measurement system output (applying either a sinusoidal signal or a step change as the known input signal)

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Calibration

- **Static Sensitivity:** The slope of a static calibration curve
- The static sensitivity, K, at any particular static input value, x1:

$$K = K(x_1) = \left(\frac{dy}{dx}\right)_{x=x_1}$$

- The static sensitivity is a measure relating the change in the indicated output associated with a given change in a static input.

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Range

- **Operating range:** A calibration applies known inputs ranging from the minimum to the maximum values for which the measurement system is to be used.
- The input operating range is defined as extending from x_{min} to x_{max}:

$$r_i = x_{max} - x_{min}$$

- This is equivalent to specifying the output operating range from y_{min} to y_{max}.
- The output span or full-scale operating range (FSO): expressed as

$$r_o = y_{max} - y_{min}$$

- It is important to avoid extrapolation beyond the range of known calibration during measurement

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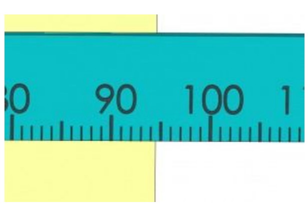
Resolution

- The resolution represents the smallest increment in the measured value that can be discerned.
- In terms of a measurement system, it is quantified by the smallest scale increment or least count (least significant digit) of the output readout indicator.
- Resolution is the smallest difference in dimensions that the measuring instrument can detect or distinguish



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Accuracy and Error

- ***True value:*** The exact value of a variable
- ***Measured value:*** The value of the variables as indicated by a measurement system
- ***Accuracy of a measurement*** refers to the closeness of agreement between the measured value and the true value
  - A **qualitative** factor since the true value is rarely known exactly, and various influences have an effect on true and measured values
- An appropriate approach to stating the closeness of agreement:
  - Identifying the **measurement errors** and to quantify them by the value of their associated uncertainties
  - ***uncertainty*** is the estimated range of value of an error. We define an error, e, as the difference between the measured

value and the true value, that is

Measurement Errors

- ***Error, (e):*** the difference between the measured value and the true value,

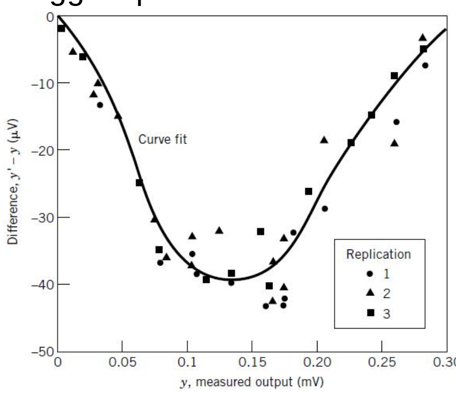
$$e = \text{Measured value} - \text{True value}$$

- Often an estimate for the value of error is based on a reference value used during the instrument's calibration as a surrogate for the true value
- A relative error based on this reference value is estimated by

$$\frac{|e|}{\text{Reference value}} \times 100$$

Deviation plot

- A special form of a calibration curve
- Curve plots the error or deviation between a reference or expected value, and the measured value, versus the measured value.
- Useful when the differences between the reference and the measured value are too small to suggest possible trends on direct calibration plots.

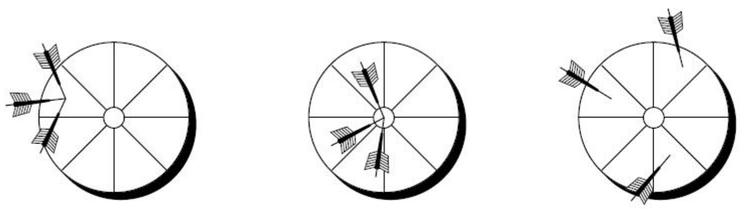


Accuracy versus Precision

- Accuracy refers to the ability to hit what is aimed at, that is the difference between the measured value and the real value
- Precision refers to the repeatability of the process that is the degree to which the instrument gives repeated measurements of the same standard.

Random and Systematic Errors

- Errors are effects that cause a measured value to differ from its true value.
- Random error causes a random variation in measured values found during repeated measurements of a variable.
- Systematic error causes an offset between the mean value of the data set and its true value.
- Both random and systematic errors affect a system's accuracy.



(a) High repeatability gives low random error but no direct indication of accuracy.

(b) High accuracy means low random and systematic errors.

(c) Systematic and random errors lead to poor accuracy.

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Bias and Random Errors

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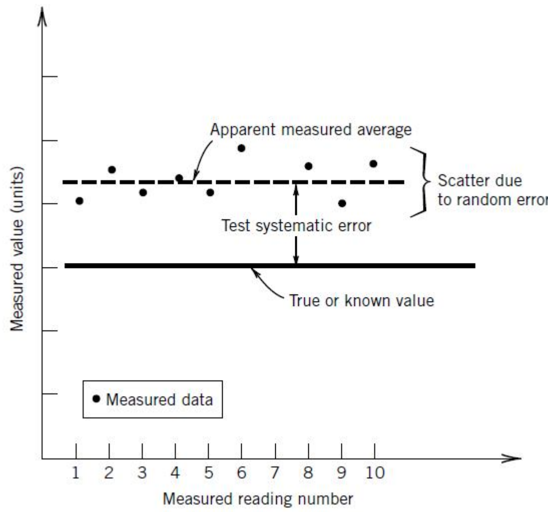
Effects of random and systematic errors on calibration readings



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Uncertainty

- A numerical estimate of the possible range of the error in a measurement.
- **Assigned uncertainty:** a plus or minus range of the indicated reading so that makes confident about the error bounds
- Uncertainty is brought about by all of the errors that are present in the measurement system—its calibration, the data set statistics, and the measurement technique.
- Individual errors are properties of the instruments, the test method, the analysis, and the measurement system.
- Uncertainty is a property of the test result.
- We might assign an estimate to the random error, **the random uncertainty**, based on the data scatter.
- The **systematic uncertainty** might be based on a comparison against a concomitant method

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Uncertainty

- The uncertainty values assigned to an instrument or measurement system specification are usually the result of several:
  - Interacting random and systematic errors inherent to the measurement system
  - The calibration procedure
  - The standard used to provide the known value

Table 1.1 Manufacturer's Specifications: Typical Pressure Transducer

Operation	
Input range	0–1000 cm H_2O
Excitation	±15 V DC
Output range	0–5 V
Performance	
Linearity error	±0.5% FSO
Hysteresis error	Less than ±0.15% FSO
Sensitivity error	±0.25% of reading
Thermal sensitivity error	±0.02%/°C of reading
Thermal zero drift	±0.02%/°C FSO
Temperature range	0–50 °C

FSO, full-scale operating range.

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Hysteresis Error

- Hysteresis error refers to differences between an upscale sequential test and a downscale sequential test
- A sequential test applies a sequential variation in the input value over the desired input range (e.g. by increasing the input value over the full input range)
- The hysteresis error of the system is estimated by its uncertainty $u_h = (y)_{\text{upscale}} - (y)_{\text{downscale}}$.
-
- Maximum hysteresis error as a percentage of full-scale output range: $\%u_{h_{\max}} = \frac{u_{h_{\max}}}{r_o} \times 100$
- Occurring when the output of a measurement system is dependent on the previous value indicated by the system (such as friction or viscous damping in moving parts or residual charge in electrical components)

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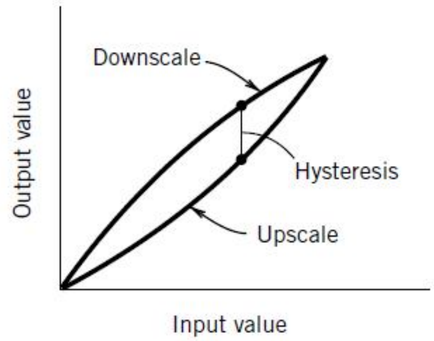
Hysteresis Error



(a) Hysteresis error

- Hysteresis affects the repeatability of the system

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Random Test

- A random test applies a random order in the values of a known input over the intended calibration range.
- Reducing the impact of interference; breaking up hysteresis effects and observation errors; reducing calibration systematic error, converting it to random error.
- Linearity error, sensitivity error, zero error, and instrument repeatability error can be quantified from a static random test calibration.

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Linearity Error

- Many instruments are designed to achieve a linear relationship between the applied static input and indicated output values.

$$y_L(x) = a_0 + a_1 x$$

- In real systems, truly linear behavior is only approximately achieved.
- A measure of the linearity error $u_L(x) = y(x) - y_L(x)$
- The maximum expected linearity error as a percentage of full-scale output range:

$$\%u_{L_{max}} = \frac{u_{L_{max}}}{r_o} \times 100$$

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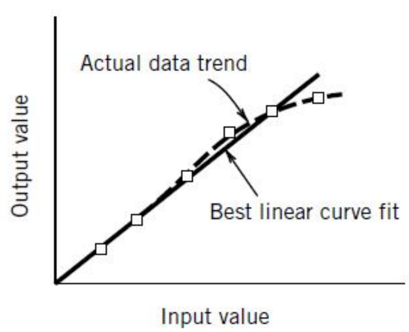
Linearity Error



(b) Linearity error

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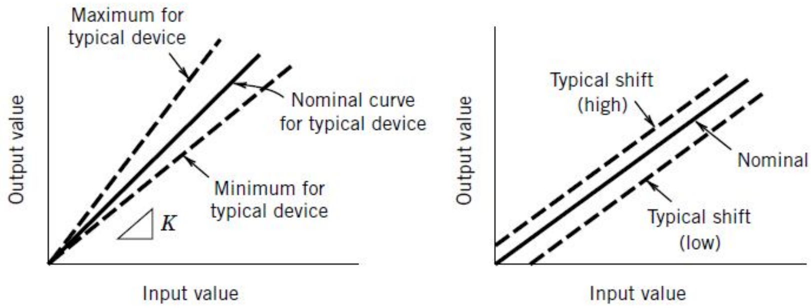
Sensitivity and Zero shift Errors



(c) Sensitivity error

(d) Zero shift (null) error

- Sensitivity error: is a statistical measure of the random error in the estimate of the slope of the calibration curve
- Zero shift error: a vertical shift of the calibration curve
- Zero error can usually be reduced by periodically adjusting the output from the measurement system under a zero input condition.

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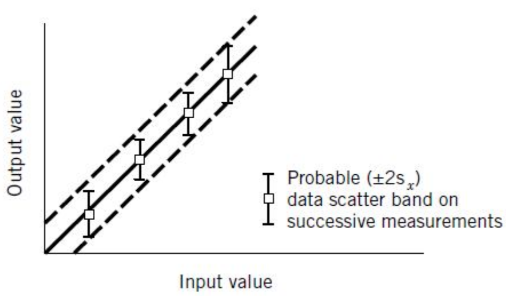
Instrument Repeatability



(e) Repeatability error

$$\%u_{R_{max}} = \frac{2s_x}{r_o} \times 100$$

- The ability of a measurement system to indicate the same value on repeated but independent application of the same input
- Repeatability is based on a statistical measure (the standard deviation, s_x, a measure of the variation in the output for a given input).

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Overall Instrument Error and Instrument Uncertainty

- An estimate of the overall instrument error is made by combining the estimates of all known errors into a term called the instrument uncertainty.
- The estimate is computed from the square root of the sum of the squares of all known uncertainty values.
- For M known errors, the overall instrument uncertainty, uc, is estimated by:

$$u_c = \left[u_1^2 + u_2^2 + \cdots + u_M^2\right]^{1/2}$$

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