Chapter 1

Basic Concepts of Measurement Methods

RS Figliola and DE Beasley; Theory and Design for Mechanical Measurements; 2000

Basic Concepts of Measurement Systems

**Definitions:**
- A *measurement* assigns a specific value to a physical variable.
- The *physical variable* becomes the measured variable.
- A *measurement system* is a tool used to quantify the physical variable.

Four Parts of Measurement System

- Sensor-Transducer Stage
- Signal Conditioning Stage
- Output Stage
- Feedback Control Stage
Definitions

- The **sensor** is a physical element that uses some natural phenomenon to sense the variable being measured.
- The **transducer** changes this sensed information into a detectable signal form (electrical, mechanical, optical, etc.)
- The goal is to convert the sensed information into a form that can be easily quantified.
Intermediate Stage

- Signal conditioning equipment modifies the transducer signal to a desired form.
- This optional intermediate stage can be used to increase the magnitude of the signal through amplification, remove portions of the signal through some filtering technique, provide mechanical or optical linkage between the transducer and the output range, or other similar activities.

Feedback-Control Stage

- In those measurement systems involved in process control, a fourth stage, called the feedback-control stage, contains a controller that interprets the measured signal and makes a decision regarding the control of the process.
- This decision creates a change in a process parameter that affects the magnitude of the sensed variable.

Experimental design involves developing a measurement test plan.
**Q: What makes up a measurement test plan?**

1. **Parameter Design Plan**: Defines test objective and identifies process variables, parameters, and a means of their control.

2. **System and Tolerance Design Plan**: Selection of measurement technique, equipment, and test procedure based on some preconceived tolerance limit of error.

3. **Data Reduction Design Plan**: How the data will be analyzed, presented, and used.

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**Variable Definitions:**

- **Independent Variable** – can be changed independent of others
- **Dependent Variable** – is affected by change in one or more other variables
- **Control of Variables** – hold at constant value or prescribed condition over duration of measurement
- **Discrete Variable** – possible values can be enumerated (dice)
- **Continuous Variable** – values can take on any level within range of operation (pressure, temperature)
- **Extraneous Variables** – cannot be controlled during measurement but affect the measured variable (operator or machine particular functioning)
More Definitions:

- **Parameters** - functional relationships between variables
- **Control Parameter** - has an effect on the behavior of the measured variable and should be controlled during test period
- **Noise** - a random variation of value of the measured signal due to variation in extraneous variables
  - A completely controlled variable contains no noise
  - Most signals have some noise; the question is how much!
    - A complete control
    - Environmental conditions
    - Thermal noise
    - Radio frequency

More Definitions Con’t:

- **Interference**: produces undesirable deterministic trends on measured values, such as a sinusoidal wave superimposed on the signal path
  - Hum and acoustic feedback in PA system
    - Well-defined environmental conditions
      - AC Power 60 Hz
      - Fluorescent Lighting 120 Hz
      - Electromagnetic Interference EMI
      - Radio Frequency RF

It is a major objective to break up interference trends so that they appear as random variation in data set. These can be handled by statistics.
Random Test

Suppose \( y = f(x_a, x_b, \ldots) \rightarrow y = \text{dependent}, x_i = \text{independent} \)

But \( y \) is also influenced by extraneous variables \( z_1 \), so that \( y = F(x_a, x_b, \ldots; z_1, z_2, \ldots) \) the dependence of \( y \) on \( x_i \) can be found by holding all but one independent variable constant and varying one variable.

Extraneous variables can not be controlled, but their influence can be minimized by randomized test procedures.

Definition:

A random test is defined by a measurement matrix that sets a random order on the value of an applied independent variable.

Trends normally introduced by the coupling of a relatively slow and uncontrolled variation in the extraneous variables with a sequential application in values of the independent variable applied will be broken up.

This type of plan is effective for the local control of extraneous variables that change in a continuous manner.

Discrete extraneous variables such as instruments, test operator, test conditions, etc can be broken up using randomized test blocks.

A block is a data set whose extraneous variable is fixed over a range of independent variable applications. Subsequent block vary the extraneous variable.
Definitions

**Repetitions** – repeated measurement of dependent variable during a single test run (diameter of ball bearing batch - multiple measurement on same batch/day)

**Replication** – an independent duplication of a series of test measurements under similar operating conditions (ball bearing batch on separate day under similar conditions)

Definitions

**Calibration** – the act of applying a known input to a measurement system in order to observe the system output

The known value used for the calibration is called the **standard**.

Definitions

**Static Calibration** – value of variable remains constant during each response observation. By incrementing change in input variables and recording the output at each level, a calibration curve can be made.

**Dynamic Calibration** – determines the relationship between an input of known dynamic behavior and the measurement system output.

- Usually such calibrations involve either a sinusoidal signal or a step change as the known input signal.
- When the variables of interest are time dependent and time-based information is sought, dynamic information is needed.
**Definition**

**Calibration Curve** – describes the static input-output relationship for a measurement system and provides a means to interpret the output.

**Static Sensitivity** – slope of the static calibration curve

\[ K = \frac{dy}{dx} \text{ at } x = x_0 \]

- K may not be constant over range if curve is nonlinear.
- The static sensitivity is a measure relating the change in the indicated output associated with a given change in a static input.

**Definitions**

- **Range** - a measurement system should not be operated outside its calibration range
  - Input Span \( r_i = x_{\text{max}} - x_{\text{min}} \)
  - Output Span \( r_o = y_{\text{max}} - y_{\text{min}} \)
- **Accuracy** – can be estimated during calibration and represents the ability to indicate the true value.
- **Absolute Error** = \( \varepsilon = \text{true value} - \text{indicated value} \)
- **Percent Accuracy** = \( (1 - \frac{|\varepsilon|}{\text{true value}}) \times 100 \)
**Precision**, or repeatability, measures a system's ability to indicate a particular value upon repeated but independent applications of specific input.

**Precision Error** is the measure of random variation in repeated measurements.

The average error in a series of repeated calibration measurements defines the bias error.

**The Bias Error** is the difference between the average value and the true value.

![Diagram](image)

**Definitions**

- **Sequential Test** – incrementally varies the input value over prescribed range (ramp up or ramp down)
- **Random Test** – randomly selects input values over prescribed range (discrete or continuous values)
  - Random test minimizes interference and break up hysteresis and observation errors. It insures that each success measurement is independent of the previous.
- **Overall Instrument Error** – based on all known error!
  - \( E_c = e_1^2 + e_2^2 + e_3^2 + \ldots + e_m^2 \) (estimate)
Difference in output:
\( e_h = y_{\text{upscale}} - y_{\text{downscale}} \)

Hysteresis error:
\( \% e_{h_{\text{max}}} = \left( \frac{e_{h_{\text{max}}}}{r_o} \right) \times 100 \)
Where \( r_o = y_{\text{max}} - y_{\text{min}} \)

Predicted output:
\( y_L(x) = a_0 + a_1 x \)

Linearity Error:
\( e_L(x) = y(x) - y_L(x) \)

Maximun expected Linearity Error:
\( \% e_{L_{\text{max}}} = \left( \frac{e_{L_{\text{max}}}}{r_o} \right) \times 100 \)

Sensitivity Error:
\( e_k \), a statistical measure of precision error in estimate of slope of calibration curve. May be corrected by adjusting the gain of the system.

Zero Error:
\( e_z \), is error in output at zero input, can be compensated by adjusting the system’s zero effect.

Repeatability Error:
\( \% (e_P)_{\text{max}} = \left( \frac{2(s_x)}{r_o} \right) \times 100 \)
- 95% of observation within 2 standard deviation
- 68% within 1 observation
Standards

When measurement system is calibrated, it is compared with some standard whose value is presumably known.

There are hierarchy of standards:
- International Primary Standard
- Transfer
- Local
- Working