Generalized Performance Characteristics of Instruments

INC 100 Instrumentation and Process Control
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Introduction

- Instrument Performance Characteristics
  - Static – nonlinear or statistical effects
  - Dynamic – linear differential equations
- To make it analytically manageable
  - separate treatment
  - Semiquantitative superposition of both characteristics → overall performance
Static Characteristics

- **Static calibration**
  - All inputs (desired, interfering and modifying) except one are kept at some constant values. Then the input under study is varied over some range of constant values.
  - The input-output relationship is valid under the stated constant conditions of all the other inputs.
- **Measurement method:** ideal situation
  - “all other inputs are held constant”
- **Measurement process:** physical realization of the measurement method
Steps in Static Calibration

1. Examine the construction of the instrument and identify and list all the possible inputs.
2. Decide which of the inputs will be significant in the application for which the instrument is to be calibrated.
3. Procure apparatus that will allow you to vary all the significant inputs over the ranges considered necessary. Procure standards to measure each input.
4. By holding some inputs constant, varying others, and recording the output(s), develop the desired static input-output relations.
Measured Value VS True Value

- **true value**
  - Unknown and unknowable
  - **reference value:** obtained by an exemplar method.
  - **exemplar method**
    - A method agreed on by experts as being sufficiently accurate for the purposes to which the data ultimately will be put.

- Measurement process must be in a state of statistical control.
  - **statistical control**
    - All major inputs are control within certain limits.
    - The rests are uncontrolled and contribute a very small effect on the output.
Process Instrumentation Terminology

- **Accuracy**
  - Degree of conformity of an indicted value to a recognized accepted standard value, or *ideal value*.

- **Error**
  - Indication - *ideal value*

- **Linearity**
  - The closeness to which a curve approximates a straight line.
Nonlinearity

(a) Actual performance and worst deviation error compared to the best straight line (BSL).

(b) BSL through zero compared to the span of output.

(c) Endpoint at 100% compared to the span of input.

(d) Theoretical line compared to the span of output.
Process Instrumentation Terminology (cont.)

- **Range**
  - The region between the limits within which a quantity is measured, received, or transmitted, expressed by stating the lower and upper range-values.

- **Repeatability**
  - The closeness of agreement among a number of consecutive measurements of the output for the same value of the input under the same operating conditions, approaching from the same direction, for full range traverses.

- **Reproducibility**
  - The closeness of agreement among repeated measurements of the output for the same value of the input under the same operating conditions over a period of time, approaching from both directions.
Process Instrumentation
Terminology (cont.)

- **Resolution**
  - The least interval between two adjacent discrete details which can be distinguished one from the other.
  - Limitation: *noise floor* of the instrument

- **Hysteresis**
  - The noncoincidence of loading and unloading curves
    - internal friction of stressed parts (mainly the spring)
    - External sliding friction e.g. free play or looseness in the mechanism of an instrument
Process Instrumentation Terminology (cont.)

- **Span**
  - The algebraic difference between the upper and lower range-values.

- **Sensitivity**
  - The ratio of the change in output magnitude to the change of the input which causes it after the steady-state has been reached.
Static Sensitivity

- Drifts
  - Zero drift
  - Sensitivity drift or scale-factor drift
Expressing Static Sensitivity

- One component of the overall accuracy
- The maximum deviation of the calibration curve from a straight line drawn between no-load and full-scale load outputs.
Dynamic Characteristics

- Time constant
- Rise time
- Settle time
- Overshoot
- Frequency response
  - Filtering characteristics
  - Natural frequencies
Zero-Order Instrument
First-Order Instrument
Second-Order Instrument
Generalized Configurations and Functional Descriptions of Measuring Instruments

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Functional Elements of An Instrument

- to present the concept of functional element, and not as a physical schematic of a generalized instrument.
- A given instrument may in value the basic function in any number and combinations they need not exist or appear in the order.
- A physical component may serve several of the basic functions.
Functional Elements

- Primary sensing element
  - first receives energy from the measured medium and produces an output depending, in the same way, on the measured quantify (measurand).
  - An instrument always extracts some energy from the measured medium. Thus the measured quantify is always disturbed by the act of measurement, which makes a perfect measure theoretically impossible.
  - Good instruments are designed to minimize this loading effect.
Functional Elements (cont.)

- Variable-conversion element
  - convert the output signal of the primary sensing element to another more suitable variable, while preserving the information content of the original signal.

- Variable-manipulation element
  - change, in numerical value according to some definite rule but a preservation of the physical nature of the variable, e.g. an electronic amplifier (analog).
Functional Elements (cont.)

- **Data-transmission element**
  - when the functional elements are separated, it becomes necessary to transmit the data from one to another.

- **Data-presentation element**
  - presents the information about the measured quantity to one of the human senses.

- **Data-storage/playback element**
  - Storage-pen/ink
  - Storage/playback – Tape recorder/reproducer, memory
An Example of Functional Elements of an Instrument
Functional Elements of Pressure Gauge
Functional Elements of Pressure
Thermometer
Active and Passive Transducers

- **energy** consideration
  - How the transducer interact with the environment they are measureing
- A physical component may act as an active transducer or a passive transducer.
- A passive transducer
  - a component whose output energy is supplied entirely or almost entirely by its input signal
- An active transducer
  - has an auxiliary source of power which supplied a part of the output power while the input signal only an insignificant portion.
  - the input controls the output but does not act supply the output power.
  - Using **feedback** principle
Examples of Active Transducer
Analog and Digital Modes of Operation

- Analog
  - By nature

- Digital
  - More robust against noises

In combined analog/digital system,
- the digital portions need not limit system accuracy.
- These limitations generally are associated with the analog portions and/or the A/D conversion devices.
Null and Deflection Methods

- In deflection-type device,
  - the measured quantity produces some physical effect that engenders a similar but opposing effect in same part of the instrument.
  - The opposing effect increases until balance is achieved, at which point deflection is measured and the value of measured quantity inferred.

- In null-type device,
  - attempts to maintain deflection at zero by suitable application an effect opposing that generated by the measured quantity.
  - Not suitable for dynamic measurement (fluctuating).
Null and Deflection Methods (cont.)

For most measurements in general, the accuracy attainable by the null method is of a higher level than by the defection method.

- the opposing effect of the deflection type must be calibrated by a standard (it is not itself a standard) while in the null instrument a direct comparison of the unknown variable with the standard is achieved.

- Null methods – the detector of unbalance can be made very sensitive, balance it need cover only a small range around zero also, the detector need not be calibrated since it must detect on the presence and direction of unbalance.
Example of Null and Deflection Methods
Input-Output Configuration of Instruments
Input-Output Configuration of Instruments

- Types of Inputs
  - Desired inputs
  - Interfering inputs
  - Modifying inputs
    - Quantities that cause a change in the input-output relations for the desired and interfering inputs

- Input-output relations
  - Constant
  - Nonlinear static function
  - Differential equation
  - Probability density function → description of output from repeated equal static input.
Examples of Results from Different Inputs
Methods of Correction for Interfering and Modifying Inputs

- method of inherent sensitivity
- method of high-gain feedback
- method of calculated output corrections
- method of signal filtering
- method of opposing inputs
Method of Inherent Sensitivity

- Try to make $F_I$ and $F_{M,D}$ as nearly to zero as possible.
- e.g. using a material that has low temperature coefficient of resistance for strain gauge.
Method of High-Gain Feedback

- **Open-loop**
  \[ x_0 = (K_{Mo} K_{SP}) e_i \]

- **Closed-loop**
  \[ x_0 = \frac{K_{AM} K_{Mo} K_{SP}}{1 + K_{AM} K_{Mo} K_{SP} K_{FB}} e_i \]

  \[ K_{AM} K_{Mo} K_{SP} K_{FB} \approx 1, \]

  \[ x_0 = \frac{1}{K_{FB}} e_i \]
Method of Calculated Output Corrections

- Requires to measure or estimate the magnitudes of the interfering and/or modifying inputs.
- With sensors for the spurious inputs, an automatic correction can be done ➔ smart sensor.
Method of Signal Filtering
Examples of Signal Filtering
Method of Opposing Inputs

Unavoidable interfering input

\( i_{I1} \rightarrow F_{I1} \rightarrow o_{I1} \)

Intentionally introduced interfering input

\( i_{I2} \rightarrow F_{I2} \rightarrow o_{I2} \)

Desired input

\( i_D \rightarrow F_D \rightarrow o_D \)

\( o_{I1} - o_{I2} \) essentially zero

Output

\( + \)
Examples of Opposing Inputs
Measurement Standards

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Definition

- devices, artifacts, procedures, instruments, systems, protocols, or processes that are used to define (or to realize) measurement units and on which all lower echelon (less accurate) measurements depend.
- may also be said to store, embody, or otherwise provide a physical quantity that serves as the basis for the measurement of the quantity.
- the physical embodiment of a measurement unit, by which its assigned value is defined, and to which it can be compared for calibration purposes. In general, it is not independent of physical environmental conditions, and it is a true embodiment of the unit only under specified conditions.
- a unit of known quantity or dimension to which other measurement units can be compared.
The Need for Standards

- Standards define the units and scales in use, and allow comparison of measurements made in different times and places.
A Historical Perspective

- to serve needs of commerce, trade, land division, taxation and scientific advances.
- The earliest standards were based on the human body, and then attempts were made to base them on “natural” phenomena.
Examples

- **Length**
  - a fraction of the circumference of the earth but maintained by the use of a platinum/iridium bar.
  - Now, the meter is the distance that light travels in a vacuum in an exactly defined fraction (1/299,792,458) of a second.

- **Time**
  - defined as a fraction of the day but maintained by a pendulum clock.
  - the second is maintained by atomic clocks
A Conceptual Basis of Measurements

Quality

is based upon

Valid Decisions

are based upon

Correct Numerical Data

are based upon

Accurate Measurements

are based upon

Calibrated Instruments (Properly Utilized)

are based upon

Traceable Standards
# The SI Base Units

<table>
<thead>
<tr>
<th>Base quantity</th>
<th>Name of Base Unit</th>
<th>Symbol</th>
</tr>
</thead>
<tbody>
<tr>
<td>Length</td>
<td>meter</td>
<td>m</td>
</tr>
<tr>
<td>Mass</td>
<td>kilogram</td>
<td>kg</td>
</tr>
<tr>
<td>Time</td>
<td>second</td>
<td>s</td>
</tr>
<tr>
<td>Electric current</td>
<td>ampere</td>
<td>A</td>
</tr>
<tr>
<td>Thermodynamic temperature</td>
<td>kelvin</td>
<td>K</td>
</tr>
<tr>
<td>Amount of substance</td>
<td>mole</td>
<td>mol</td>
</tr>
<tr>
<td>Luminous intensity</td>
<td>candela</td>
<td>cd</td>
</tr>
</tbody>
</table>
The International Definitions of the SI Base Units

unit of length (meter)
- The meter is the length of the path traveled by light in vacuum during a time interval of \(1/299\,792\,458\) of a second
- Note: The original international prototype, made of platinum-iridium, is kept at the BIPM.

unit of mass (kilogram)
- The kilogram is the unit of mass: it is equal to the mass of the international prototype of the kilogram.
unit of time (second)

- The second is the duration of 9 192 631 770 periods of the radiation corresponding to the transition between the two hyperfine levels of the ground state of the cesium-133 atom

unit of electric current (ampere)

- The ampere is that constant current which, if maintained in two straight parallel conductors of infinite length, of negligible cross section, and placed 1 meter apart in vacuum, would produce between these conductors a force equal to 2x10^{-7} newton per meter of length.
The International Definitions of the SI Base Units (cont.)

Unit of thermodynamic temperature (kelvin)

- The kelvin, unit of thermodynamic temperature, is the fraction $1/273.16$ of the thermodynamic temperature of the triple point of water.

Unit of luminous intensity (candela)

- The candela is the luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency $540 \times 10^{12}$ hertz and that has a radiant intensity in that direction of $(1/683)$ watt per steradian.
The International Definitions of the SI Base Units (cont.)

unit of amount of substance (mole)

1. The mole is the amount of substance of a system which contains as many elementary entities as there are atoms in 0.012 kilogram of carbon-12.

2. When the mole is used, the elementary entities must be specified and may be atoms, molecules, ions, electrons, other particles, or specified groups of such particles.

In the definition of the mole, it is understood that unbound atoms of carbon-12, at rest, and in their ground state, are referred to.
### SI Derived Units with Special Names

<table>
<thead>
<tr>
<th>Derived quantity</th>
<th>Name</th>
<th>Symbol</th>
<th>Expressed in Terms of Other Units</th>
<th>Expressed in Terms of SI Base Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Plane angle</td>
<td>radian</td>
<td>rad</td>
<td></td>
<td>m m⁻¹</td>
</tr>
<tr>
<td>Solid angle</td>
<td>steradian</td>
<td>sr</td>
<td></td>
<td>m² m⁻²</td>
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<tr>
<td>Frequency</td>
<td>hertz</td>
<td>Hz</td>
<td></td>
<td>s⁻¹</td>
</tr>
<tr>
<td>Force</td>
<td>newton</td>
<td>N</td>
<td></td>
<td>m kg s⁻²</td>
</tr>
<tr>
<td>Pressure, stress</td>
<td>pascal</td>
<td>Pa</td>
<td>N m⁻²</td>
<td>m⁻¹ kg s⁻²</td>
</tr>
<tr>
<td>Energy, work, quantity of heat</td>
<td>joule</td>
<td>J</td>
<td></td>
<td>m² kg s⁻²</td>
</tr>
<tr>
<td>Power, radiant flux</td>
<td>watt</td>
<td>W</td>
<td></td>
<td>m² kg s⁻³</td>
</tr>
<tr>
<td>Electric charge, quantity of electricity</td>
<td>coulomb</td>
<td>C</td>
<td></td>
<td>s A</td>
</tr>
<tr>
<td>Electric potential, potential difference,</td>
<td>volt</td>
<td>V</td>
<td>W/A</td>
<td>m² kg s⁻³ A⁻¹</td>
</tr>
<tr>
<td>electromotive force</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Capacitance</td>
<td>farad</td>
<td>F</td>
<td>C/V</td>
<td>m⁻² kg⁻¹ s⁴ A²</td>
</tr>
<tr>
<td>Electric resistance</td>
<td>ohm</td>
<td>Ω</td>
<td>V/A</td>
<td>m² kg s⁻³ A⁻²</td>
</tr>
<tr>
<td>Electric conductance</td>
<td>siemens</td>
<td>S</td>
<td>A.V</td>
<td>m⁻² kg⁻¹ s³ A²</td>
</tr>
<tr>
<td>Magnetic flux</td>
<td>weber</td>
<td>Wb</td>
<td>V s</td>
<td>m² kg s⁻² A⁻¹</td>
</tr>
<tr>
<td>Magnetic flux density</td>
<td>tesla</td>
<td>T</td>
<td>Wb/m²</td>
<td>kg s⁻² A⁻¹</td>
</tr>
<tr>
<td>Inductance</td>
<td>henry</td>
<td>H</td>
<td>Wb/A</td>
<td>m² kg s⁻² A⁻²</td>
</tr>
<tr>
<td>Celsius temperature</td>
<td>degree Celsius</td>
<td>°C</td>
<td></td>
<td>K</td>
</tr>
<tr>
<td>Luminous flux</td>
<td>lumen</td>
<td>lm</td>
<td>cd sr</td>
<td>cd m² m⁻² = cd</td>
</tr>
<tr>
<td>Illuminance</td>
<td>lux</td>
<td>lx</td>
<td>m⁻² cd sr</td>
<td>m⁻² cd</td>
</tr>
<tr>
<td>Activity (referred to a radio nuclide)</td>
<td>becquerel</td>
<td>Bq</td>
<td></td>
<td>m⁻¹</td>
</tr>
<tr>
<td>Absorbed dose, specific energy imparted,</td>
<td>gray</td>
<td>Gy</td>
<td>J/kg</td>
<td>m²s⁻²</td>
</tr>
<tr>
<td>kerma</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Dose equivalent, ambient dose equivalent,</td>
<td>sievert</td>
<td>Sr</td>
<td>J/kg</td>
<td>m²s⁻²</td>
</tr>
<tr>
<td>organ equivalent dose</td>
<td></td>
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</tr>
</tbody>
</table>

*Note that when a unit is named after a person the symbol takes a capital letter and the name takes a lowercase letter.*