FACULTY OF MECHANICAL ENGINEERING

# SKMM 1912 EXPERIMENTAL METHODS

UNIVERSITI TEKNOLOGI MALAYSIA

# CONCEPT OF MECHANICAL MEASUREMENT

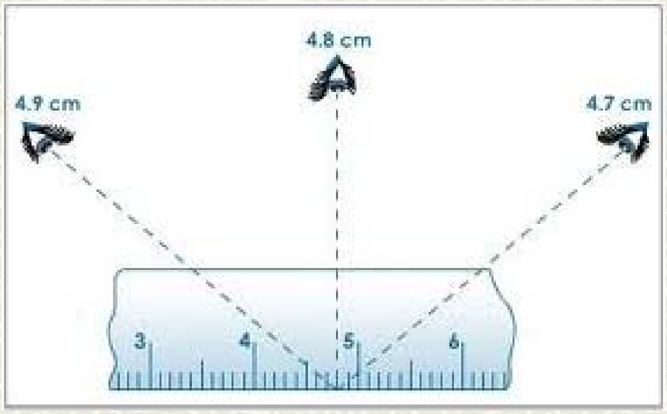
- The heart of the hardware for experimentation is the measurement system
- The proper design and application of the measurement system is vital to the success of any experimental study.

# CONCEPT OF MECHANICAL MEASUREMENT

- To design and apply measurement systems, we need two kinds of information;

1. we must be familiar with *accepted methods* of specifying the *accuracy* of any measurement system. (The accuracy of a measurement system refers to its ability to indicate a true value exactly).
2. we must be aware of the different devices available for measuring specific variables such as temperature, acceleration, pressure, and voltage, so that we can *choose the most appropriate* for our apparatus

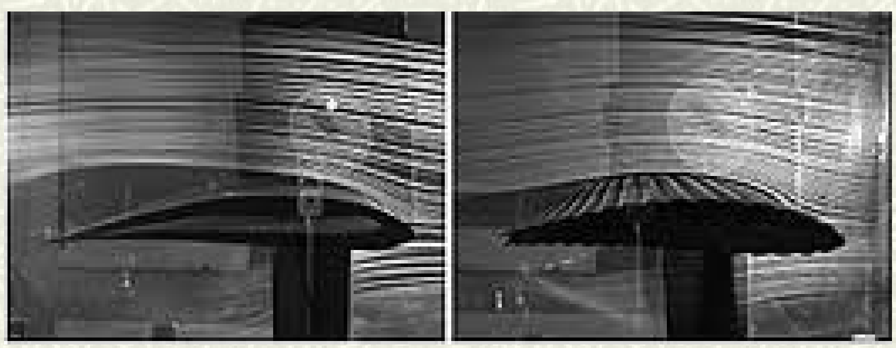
# CONCEPT OF MECHANICAL MEASUREMENT






# CONCEPT OF MECHANICAL MEASUREMENT

- Designing a measurement system means using suitable techniques, using acceptable devices, making validation testing, making suitable calibration, and planning on how to handle, analyze and present measured data.
- Usually we need to know what to measured first? Then we can decide the apparatus/devices required for the test and measurement



# CONCEPT OF MECHANICAL MEASUREMENT

- Regardless of the measurement system design, the following items should be followed to minimize errors;
  - if several parameters need to be controlled, experimental procedure must be so designed that changes in one parameter would not influence the value of other parameters. If unable to do so, the number of influencing parameters should be reduced.

# CONCEPT OF MECHANICAL MEASUREMENT

- measurement should be designed so that the variable being measured is the only dependent variable during the measurement. Others variables have to be controlled.
- measuring detectors/devices must be sensitive enough to detect any changes in the variable being measured but not the other variables
- signal path of a measurement system must be so designed that effects of foreign or external variables can be minimized
- Experimental plan must be so designed that effects of foreign variables are only due to random occurrences

# BASIC DEFINITIONS

- When measuring, input signal is not known before hand but generated as output signal.
- But signal output can be influenced by many variables that result in distortion.
- Careful planning is need to minimize such influence.
- Only during calibration one can input values can be known beforehand and the information can be used to relate input signal and output signal.
- One important step in designing measurement system is finding the way to do repeatable calibration that can best simulate the input signal during the actual measuring

# BASIC DEFINITIONS

- Data
  - Raw values obtained from experiment. Normally numerical values
- Population
  - Collection of raw values – finite or infinite values
- Sample
  - Part of population – collection of values obtained by experiment, finite and can represent the population

# BASIC DEFINITIONS

- True value
  - Actual magnitude of measured entity eg pressure, velocity, temperature, etc. Actual value can be estimated but never known exactly.
- Indicated value
  - Value as displayed by measurement system. It is the source of raw data.

# BASIC DEFINITIONS

- Resolution
  - Equipment resolution refers to the smallest scale readable from the equipment. For instance, a thermometer that can give reading between 0° C and 100° C on 12-inch scale can have higher resolution compared to a similar thermometer but on a 6-inch scale.

# BASIC DEFINITIONS

- Error
  - In measurement system, it is logical to define error as the difference between the reading of the instrument and the true value of the measured quantity.
  - Error is the difference between actual value ($V_a$) and result ($V_r$).

$$Error = V_r - V_a$$

  - However, the nature of parameters involved in error calculations is difficult to ascertain, so the actual value of error is rarely known for sure.

# BASIC DEFINITIONS

- In some situations, error is measured in term of fraction error

$$\textit{fraction error} = \frac{\textit{quantity error}}{\textit{size of quantity}}$$

- And most commonly used method is percentage error

$$\textit{Percentage error} = \frac{\textit{quantity error}}{\textit{size of quantity}} \times 100$$

- As an example, pressure p is mentioned as 1.5 bar may have error expressed as ± 5%; so p = 1.5 ± 0.075. .

# CALIBRATION

# CALIBRATION

- A calibration is the act of *applying a known value* to the *input* of a measuring instrument for the purpose of observing the *output*.
- Calibration affords the opportunity to check the measurement instrument against a *known standard*, and subsequently to reduce error.
- However, the exact true value won't be known because calibration involves comparison between an instrument and the standard. The standard, itself being a physical devices, is also not perfect. Thus, it is incapable of telling us the the true value.

# CALIBRATION

- Calibration procedures involve a comparison of the particular instrument with either ;
  - a *primary standard*
  - a *secondary standard* with a higher accuracy than the instrument to be calibrated
  - a *known input* source

# CALIBRATION

- A flowmeter, for instance, can be calibrated by;
  - comparing it with a standard flow-measurement facility at SIRIM, British Standard Institute (BSI), or National Institute of Standards & Technoloy (NIST), or
  - comparing it with another flowmeter of known accuracy, or
  - directly calibrating with a primary measurement such as weighing a certain amount of water in a tank and recording the time elapsed for this quantity to flow through the meter.

# CALIBRATION CONCEPT

- A calibration is the *act of applying a known value* to the *input* of the measuring system for the purpose of observing *the system output*
- The known value applied to the input is known as the *standard*
- The *relationship between the input (independent variables) and the output (dependent variables)* of the measuring system is established during the calibration of the measuring system.

# CALIBRATION CONCEPT

- By application of a range of known values to the input and observation of the system output, a *direct calibration curve* can be developed for the measurement system.
- On such a curve the input $x$ is plotted on the abscissa against the measurement output $y$ on the ordinate.
- In a calibration the input value should be a *controlled input variable*, while the measured output value becomes the *dependent variable of the calibration*.

# CALIBRATION CONCEPT

- A calibration curve forms the logic by which a measurement system's indicated output can be interpreted during an actual measurement.
- Alternatively, a calibration curve can be used as part of developing a functional relationship, an equation known as a correlation, between input and output.

# CALIBRATION CONCEPT

- A correlation will have the form $y = f(x)$ and is determined by applying physical reasoning and curve fitting techniques to the calibration curve.
- The correlation can then be used in later measurements to ascertain the unknown input value based on the output value, the value indicated by the measurement system.

# STATIC CALIBRATION

- most common type of calibration
- a known value is input to the system under calibration and the system output is recorded
- term ‘static’ refers to a *calibration procedure in which the values of the variables remain constant during a measurement*, that is they do not change with time
- in static calibration, only the magnitudes of the known input and the measured output are important.

# DYNAMIC CALIBRATION

- In a broad sense, *dynamic calibration are time dependent in both their magnitude and frequency content.*
- The input-output magnitude relation between a dynamic input signal and a measurement system will depend on the time-dependent of the input signal.
- When time-dependent variables are to be measured, a dynamic calibration is performed in addition to the static calibration.
- A dynamic calibration determines the relationship between an input of known dynamic behavior and the measurement system output

# SENSITIVITY

- Sensitivity
  - The slope of a static calibration curve yields the static sensitivity of the measurement system.
  - As shown graphically in the calibration curve of figure 2.1, the static sensitivity, K, at any particular static input value, say $x_1$, is evaluated by

$$K = K_{(x1)} = (dy/dx)_{x=x1}$$

  - The static sensitivity is a *measure relating the change in the indicated output associated with a given change in a static input.*
  - Another definition of Sensitivity is the smallest change in measurement that a measuring equipment can detect

# SENSITIVITY

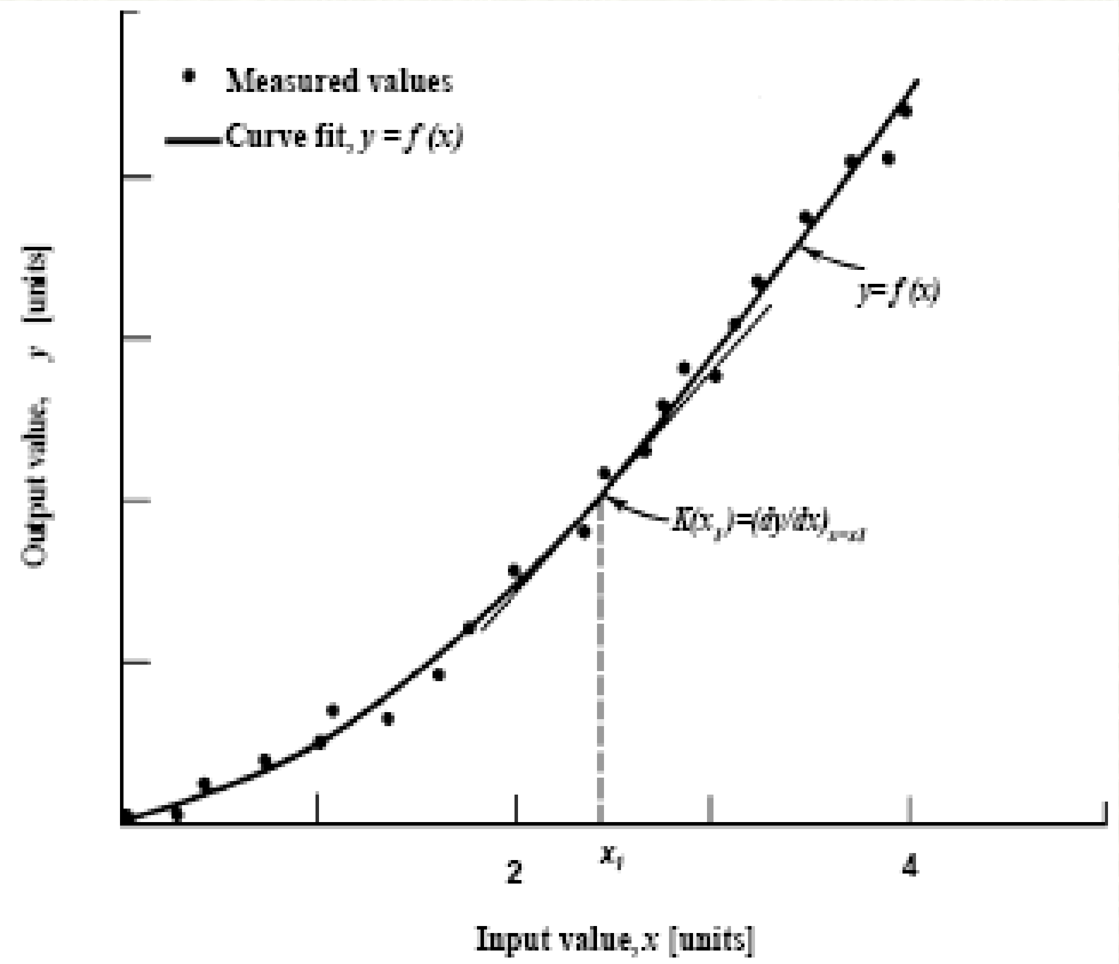



Figure 2.1

# RANGE

- Range
  - the proper procedure for calibration is to apply known input ranging from the minimum and to the maximum values for which the measurement system is to be used.
  - these limits define the operating range of the system
  - The input operating range is defined as

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

# RANGE

- Similarly, the output operating range is defined as

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

- It is important to avoid extrapolation beyond the range of known calibration during measurement since the behavior of the measurement system is uncharted in these regions.

# ACCURACY

- Accuracy
  - The accuracy of a system can be estimated during calibration
  - If we assume that the input value is known exactly, then the known input value can be called the true value
  - The accuracy of a measurement system refers to its ability to indicate a true value exactly.

# ACCURACY

- Accuracy is related to absolute error
- Absolute error, e, is defined as the difference between the true value applied to a measurement system and the indicated value of the system:

$$e = \text{true value} - \text{indicated value}$$

# ACCURACY

- Percent relative accuracy is defined as

$$A = \left(1 - \frac{e}{\text{true value}}\right) \times 100$$

- By definition, accuracy can be determined only when the 'true value' is known, such as during a calibration

.

# PRECISION

- Precision
  - The repeatability or precision of a measurement system refers to the ability of the system to indicate a particular value upon repeated but independent applications of a specific value of input.
  - But note that a system that repeatedly indicates the same wrong value upon repeated application of a particular input would be considered to be very precise regardless of its known accuracy.

# SEQUENCE CALIBRATION

- A sequence calibration applies a sequential variation in the input value over the desired input range.
- This may be accomplished by increasing the input value (up scale direction) or by decreasing the input value (downscale direction) over the full input range.

# HYSTERESIS

- The sequence calibration is an effective diagnostic technique for identifying and quantifying hysteresis
- Hysteresis error refers to differences between an upscale sequence calibration and a downscale sequence calibration
- The hysteresis error of the system is given by

$$e_h = y_{upscale} - y_{downscale}$$

- The effect of hysteresis in a sequence calibration curve is illustrated in figure 2.2

# HYSTERESIS

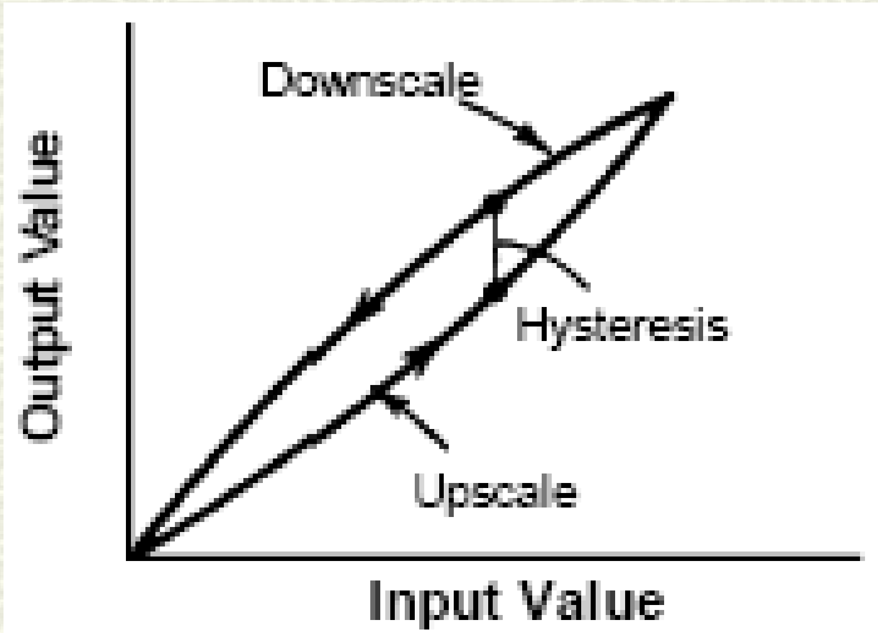



Figure 2.2

# HYSTERESIS

- Hysteresis is usually specified for a measurement system in terms of the maximum hysteresis error as a percentage of full-scale output range (FSO)

$$\%(e_h) = \frac{\left[e_h(x)\right]_{\max}}{r_o} * 100$$

# HYSTERESIS

- Hysteresis occurs when the output of a measurement system is dependent on the previous value indicated by the system.
- Such dependencies can be brought about through some realistic system limitations such as friction or viscous damping in moving parts or residual charge in electrical components.
- Some hysteresis is normal for any system and affects the precision of the system

# RANDOM CALIBRATION

- A random calibration applies a randomly selected sequence of values of a known input over the intended calibration range.
- It breaks up hysteresis effects and observation errors.
- It ensures that each application of input value is independent of the previous.
- Generally, such a random variation in input value will more closely simulate the actual measurement situation.

# RANDOM CALIBRATION

- A random calibration provides an important diagnostic test for the delineation of several measurement system performance characteristics based on a set of random calibration test data.
- In particular, linearity error, sensitivity error, zero error, and instrument repeatability error can be quantified from a static random calibration

# LINEARITY ERROR

- Many instruments are designed to achieve a linear relation between an applied static input and indicated output values.
- Such a linear static calibration curve would have the general form:

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

where the curve fit $y_L(x)$ provides a predicted output value based on a linear relation between $x$ and $y$.

# LINEARITY ERROR

- However, in real systems, truly linear behavior is only approximately achieved.
- The relation between $y_L$ $(x)$ and measured value $y(x)$ is a measure of the nonlinear behavior of a system:

$$e_L(x) = y(x) - y_L(x)$$

  where $e_L(x)$ is the linearity error
- Such behavior is illustrated in Figure 2.3 in which a linear curve has been fitted through a calibration data set

# LINEARITY ERROR

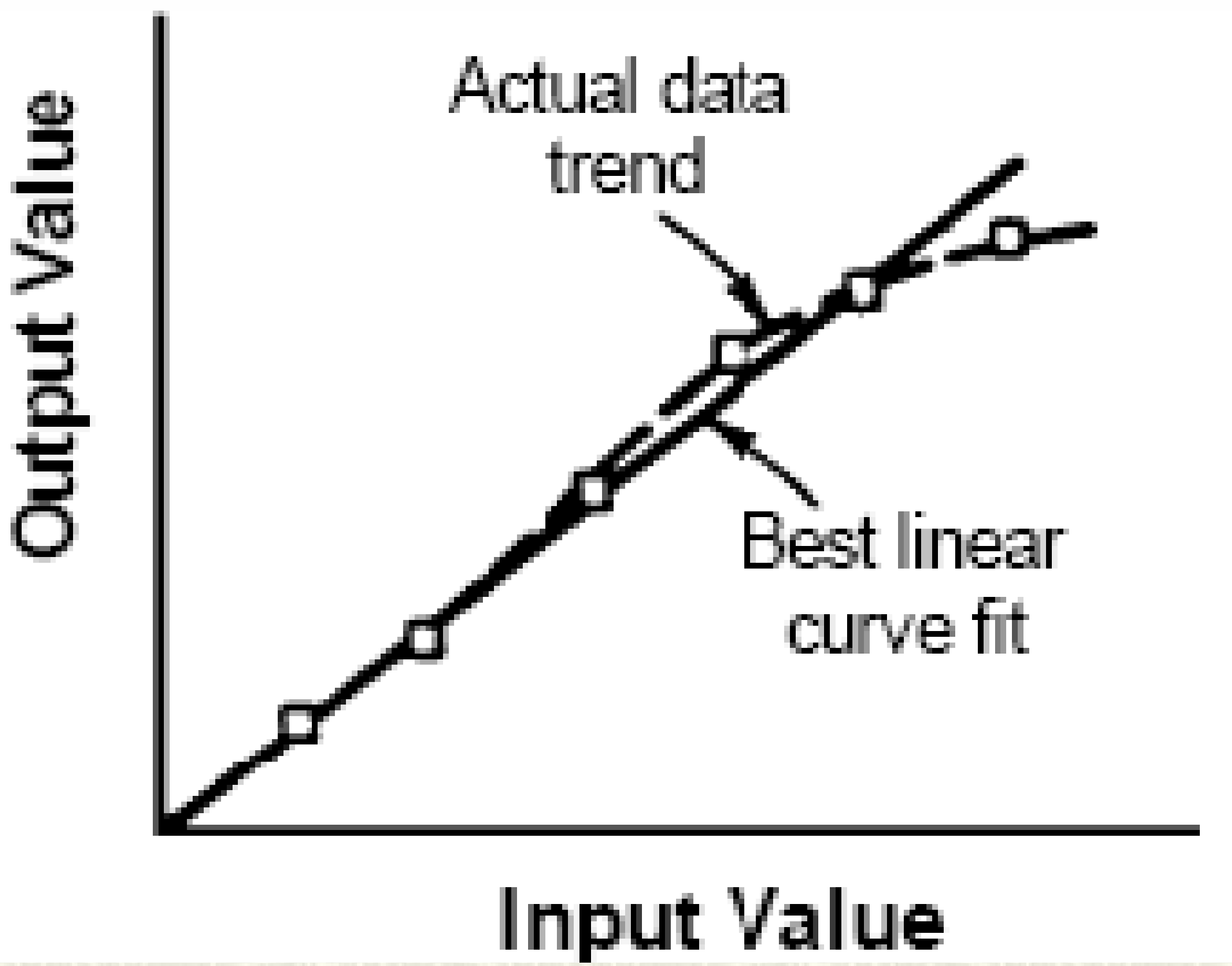



Figure 2.3

# LINEARITY ERROR

- For a measurement system that is essentially linear in behavior, the extent of possible non-linearity in a measurement device is often specified in terms of the maximum expected linearity error as a percentage of full-scale output range:

$$\%(e_L)_{\max} = \frac{[e_l(x)]_{\max}}{r_o} * 100$$

# SENSITIVITY ERROR

- The scatter in the data measured during a calibration affects the precision in the slope of the calibration curve.
- As shown in Figure 2.4, if we fix the zero intercept at zero ( a zero output from the system for zero input), then the scatter in the data leads to precision error in estimating the slope of the calibration curve.

# SENSITIVITY ERROR

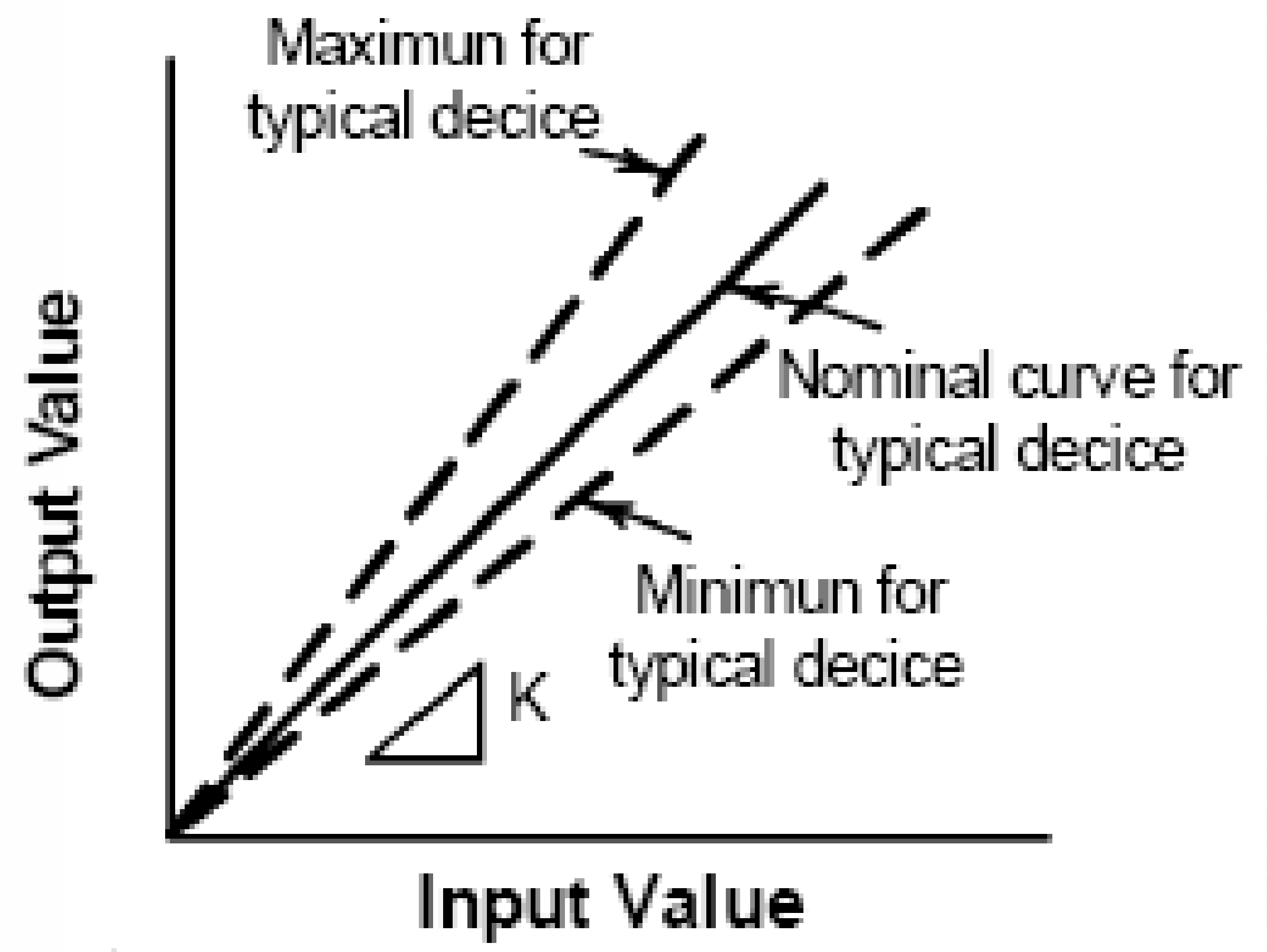



Figure 2.4

# SENSITIVITY ERROR

- The sensitivity error, $e_K$, is a statistical measure of the precision error in the estimate of the slope of the calibration curve.
- The static sensitivity of a device is also temperature dependent and this is often specified by the device manufacturer.

# ZERO ERROR

- If the zero intercept is not fixed but the sensitivity is constant, then drifting of the zero intercept introduces a vertical shift of the calibration curve, as shown in Figure 2.5.
- This shift of the zero intercept of the calibration curve is known as the zero error, $e_z$ of the measurement system.
- Zero error can usually be reduced by periodically adjusting the output from the measurement system under a zero input condition.
- However, some random variation in the zero intercept is common, particularly with electronic and digital equipment subjected to temperature variations.

# ZERO ERROR

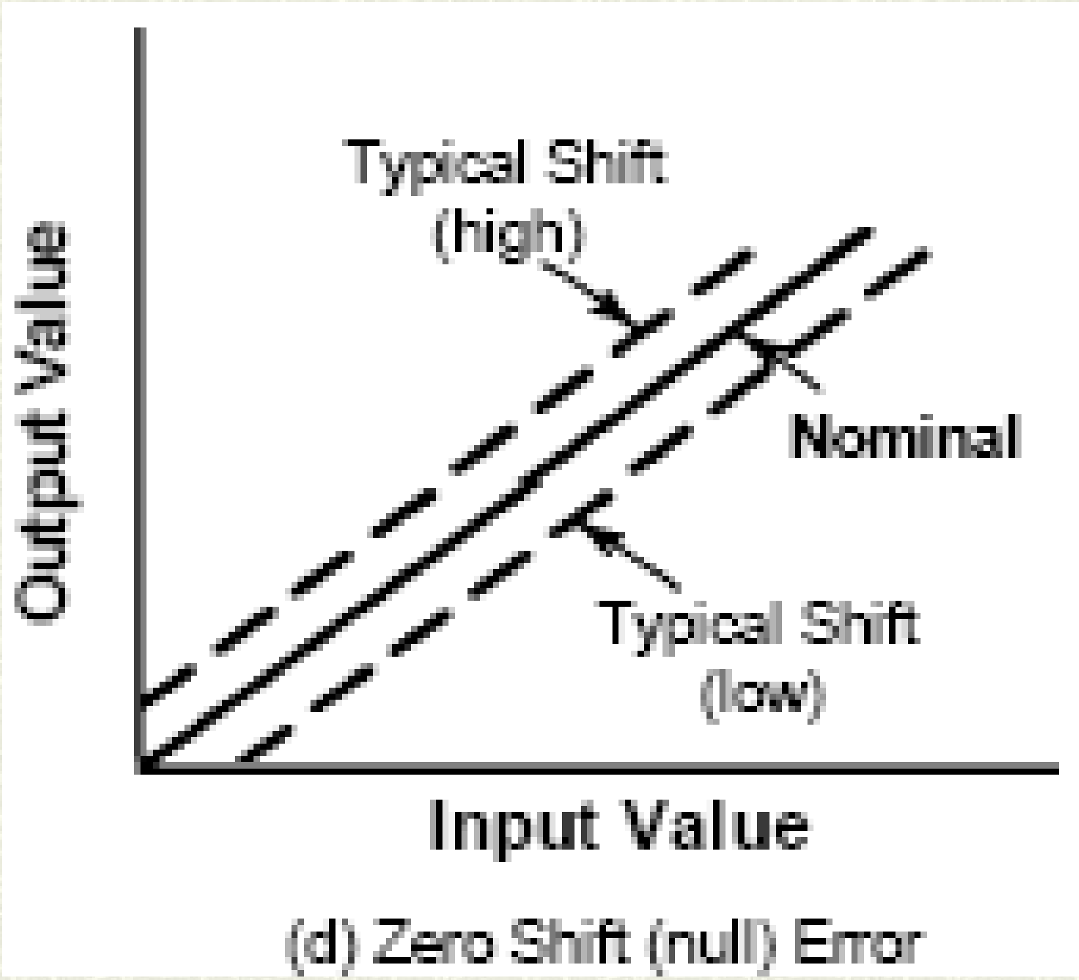



Figure 2.5

# REPEATABILITY

- The ability of a measurement system to indicate the same value upon repeated but independent application of the same input is known as the *instrument repeatability.*
- Specific claims of repeatability are based on multiple calibration tests (replication) performed within a given lab on the particular unit.
- Repeatability, as shown in Figure 2.6, is based on a statistical measure called the standard deviation, $S_X$ , a measure of the variation in the output for a given input.

# REPEATABILITY

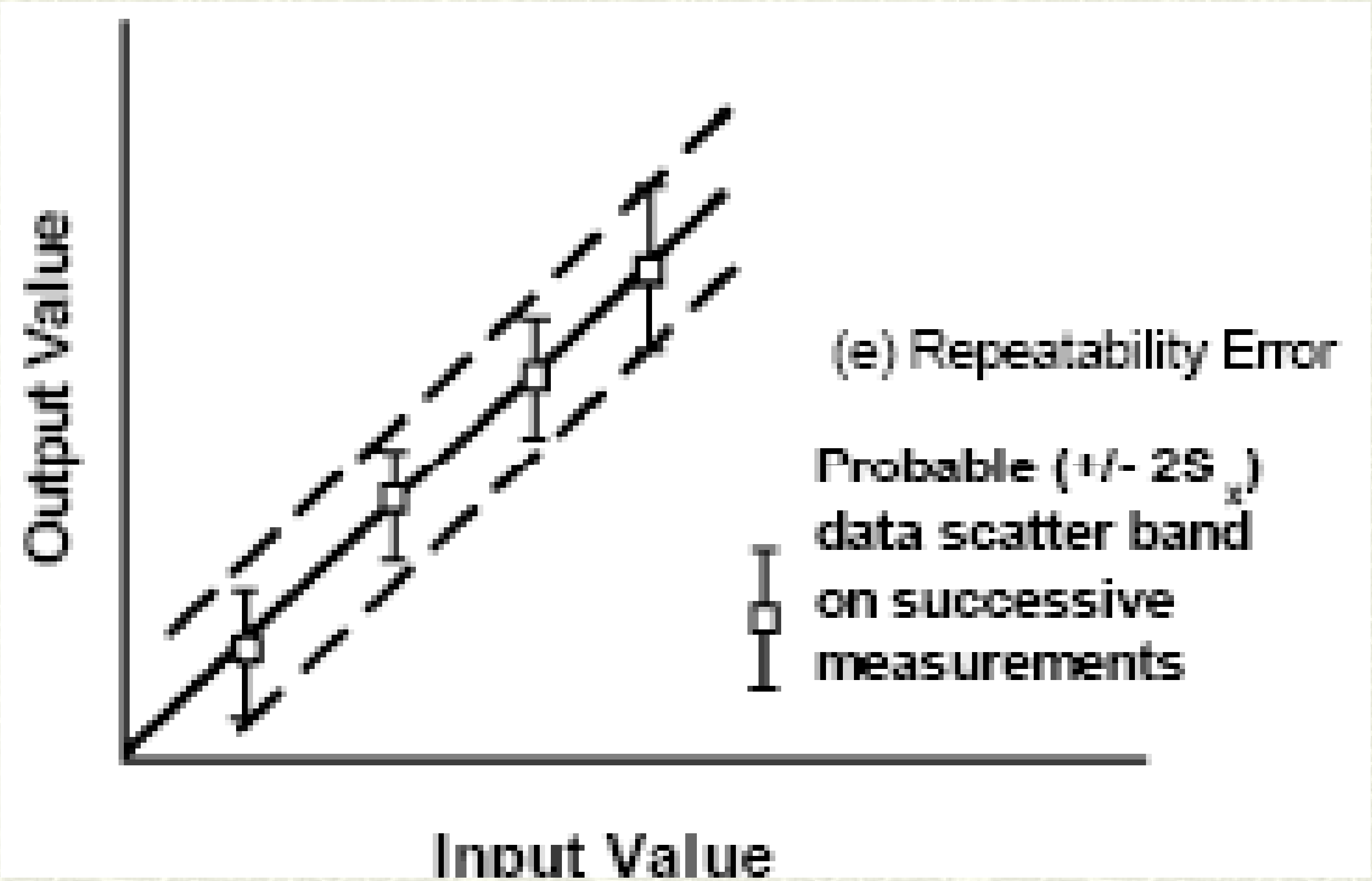



Figure 2.6

# REPEATABILITY

- The value claimed is usually in terms of the maximum expected error as a percentage of full-scale output range:

$$\%(e_r)_{\max} = \frac{2(S_x)}{r_o} * 100$$

- The instrument repeatability reflects only the error found under controlled calibration conditions. It does not include the additional errors introduced during measurement due to variation in the measured variable or due to procedure.

# STANDARD

# STANDARD

- Measurement system is calibrated by comparing it with several standards whose values are known beforehand.
- Standard that is the basis of the comparison could very well be an equipment that is well trusted by its user,
- Or, it could be an object that has well formulated physical properties to be used for comparison,
- Or, it could be a technique that has been well accepted by many, and known to produce values that can be trusted

# STANDARD

- One must be careful not to confuse the meaning of the term ‘unit’ and ‘dimension’
- A dimension is a physical variable used to specify the behaviour or nature of a particular system
- Unit is the basic term we use to measure dimension
- For instance, mass, length and time are basic dimensions that are related to unit kilogram, metre and second

# STANDARD

- Unit is defined by primary standard
- Primary standard must define each unit so that it can be exact and accurate
- Primary standard is needed, otherwise a unit can't be defined consistently – e.g a unit metre can be defined as the length of a rod, or a distance travelled by light at a specified fraction of a second.
- To avoid confusion, each unit is defined by agreements at the international level.

# STANDARD

- Some considerations for primary standards
  - Universal availabilty
  - Continuos reliability
  - Stability
  - Minimum sensitivity to surrounding environmental elements
- *International Measuring System* only provide standard for four basic dimensions – mass, length, time, and temperature
- Standard for other dimensions are derived from the four basic ones

# STANDARD

- Standard for mass

  - Dimension of mass is defined in SI system by one unit kilogram.
  - One kilogram is the mass of a platinium-iridium bar kept at the International Bureau of Weights and Measures in Sevres, France.

# STANDARD

- Standard for Length

  - Dimension of length is defined in SI system by one unit metre.
  - Primary standard being used is the one defined in 1982 where one metre is defined as distance travelled by light in vacuum in $3.335641 \times 10^{-9}$ seconds.

# STANDARD

- Standard for time

  - One second is defined as 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
  - Standard for time is maintained by Bureau Internationale de l’Heure (BIH) in Paris, France.

# STANDARD

- Standard for time

  - Meanwhile, standard for cyclical frequency is based on standard time. Standard unit is hertz

    1 Hz = 1 cycle / second

  - Cyclical frequency is related to circular frequency, whose unit is radians / second

    1 Hz = $2\pi$ radians / second

# STANDARD

- Standard for temperature
  - In 1927, US, UK and Germany proposed one standard for temperature that was later known as International Temperature Scale 1927 (ITS-27).
  - The standard, which was accepted by more than 30 nations, was almost the same as the thermodynamic scale proposed by Kelvin in 1848

# STANDARD

- Standard for temperature
  - Due to rapid development in engineering fields, several adjustments had been made especially during conferences in 1948 and 1968 where the official name of the scale was changed to International Practical Temperature Scale of 1968 (IPTS-68)
  - Now, IPTS-68 has been accepted as the primary standard for temperature by the International Committee on Weights and Measures

# STANDARD

- Standard for temperature
  - Basic unit for temperature is Kelvin (K) which is defined as 1/273.16 of thermodynamic triple point of water
  - Some countries are still using absolute Rankine (°R) scale
  - Rankine scale is related to Celcius and Farenheit scale as below;
    - °C = K – 273.15
    - °F = °R – 459.67
    - °F = 1.8 x °C + 32.0

# HIERARCHY OF STANDARD

- Primary standard serves as the ultimate reference
- However, primary standard is not practical for use in normal or day-to-day calibration
- Therefore, there is a secondary standard which is a duplicate of the primary standard
- Secondary standard provides close approximation of the primary standard and yet is more accessible for common daily use
- Besides secondary standard, there are other levels of standard as shown in the following table

# HIERARCHY OF STANDARD

| |
|---|
| Primary standard |
| National standard / mobile standard |
| Local standard |
| Work instrument / measurement system |

# HIERARCHY OF STANDARD

- Due to the nature of secondary standard as a duplicate, some amount of uncertainty exists.
- The lower we go down the hierarachy, the more errors are introduced into the standards

# HIERARCHY OF STANDARD

- The term standard can also carry a different meaning
- Standard can also means a standard testing procedure
- Standard testing procedure is to ensure consistent way to do measurement
- Example, *Power Test Code* published by *American Society of Mechanical Engineers (ASME)*

# LAB ACCREDITATION

- In Malaysia, SIRIM is responsible for maintaining secondary standards at the national level.
- In addition, some big companies or companies that are involved in the manufacture of measurement devices do have their own standards
- In Malaysia, firms that offer calibration services have to have their calibration equipment calibrated by SIRIM
- Only then, they can be recognized and qualified to offer calibration services.

# THE END