SENSA (Sensors and Actuators)

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1 Introduction

- **Sensors** generate electrical signals that contain information about a physical quantity. Electronic circuits can subsequently extract that information from the signals and show them on a display or a dial (转盘), use it in a control circuit or simply store it for later analysis.
- The inverse operation, i.e., converting an electric signal into a physical quantity, is the purpose of an **actuator**. Often the designation 'actuator' is reserved for miniature components, but this limitation is overly strict.
- 'Transducers': both sensors and actuators are transducers. → a component that performs a conversion between two (not necessarily different) types of energy. → e.g. a wheel

1.3 System analogies (类比法), effort and flow variables. 功和能流

- Energy domain: mechanical, hydraulic 液压的, thermal, electrical, magnetic, chemical, radiation…
- There exist two sets of fundamental variables that can be defined for every energy domain: power-conjugate variables and Hamiltonian or energy variables.
- **power-conjugate variables** are 2 variables that, when multiplied by each other, result in a power in the given energy domain.
- e.g. Fv, UI, torque*angular velocity, …
- **Maxwell or impedance analogy**: in which the variables are grouped as effort and flow variables. In this analogy, hydraulic, mechanic and electrical impedances are analogous. However, the network topologies are not necessarily the same in the differetn energy domains. 在这个类比中，液压和机械能和阻抗是类似的，但是拓扑结构不一定相同（串联并联等）.
- **Hamiltonian variables**: generalised displacement & momentum. The time derivative of a generalized displacement variable is a flow variable and the time derivative of a generalized momentum variable is an effort variable.
- **Ideal 1 port element**:
  a) Active ports: ideal flow source & effort source
  b) Passive ports:
     Ideal resistance 理想电阻: element that imposes a functional relationship between an effort variable and a flow variable. E.g. Ohm's law, e=Rf; one tacit requirement is R>0, means the ideal resistance only removes energy from the system (dissipation)
     Ideal inertance 理想电感: element that imposes a functional relationship between a flow variable and a generalized momentum. f=g(p), p=mv, e.g. mass 质量, inductance 电感
     Ideal capacitance 理想电容: element that imposes a functional relationship between an effort variable and a generalized displacement. e=g(q) e.g. F=Kx
- Signal conditioning: a signal conditioner is a circuit that converts a raw electrical signal

coming from a sensor into another electrical signal that is better suited to be transported, displayed, digitized or stored, e.g., amplification, level shifting, filtering, impedance matching, (de)modulation, linearization…

1.6 Static characteristics

- **Transfer function**: describes the relationship between the physical input signal and the electrical output signal. For linear sensors it suffices 足够 to specify the sensitivity + an offset (output value for a zero input value).
- **Sensitivity**: the ratio of a small change of the electrical signal to the corresponding change in the measured. → first derivative of the transfer function.
- **Range / span**: the interval within which the value of the measured must lie in order to be converted to an electrical output signal with an acceptable accuracy.
- **Accuracy**: is the expected or producer-specified maximum deviation between the real and the ideal output signal, usually calculated back to the maximum error on the measured. → can be absolute or relative or their combination
- **The systematic error**: corresponds with the difference between the real value of the measurand and the average of a large number of measurements. **The random errors** are the deviations of every individual measurement with respect to the average value of all measurements.
- **Accuracy**: measure for the maximum deviation between the measured values and the real value.
- **Precision**: measure for the deviation between and among subsequently measured values. → random error. It is important to realize that a very precise sensor is not necessarily a very
- accurate sensor, but it can be turned into an accurate sensor by calibration.
- **Resolution:** the smallest detectable variation of the measurand.
- Usually when writing down a measurement result also the (in)accuracy is mentioned, in the form: Result +/- inaccuracy

  A good engineer will take care not to use a higher number of significant digits for the result than justified by the accuracy
- **Calibration**: To eliminate or at least reduce systematic errors in a measurement process, we perform a static calibration.
  a) keeping all inputs constant except one. This input is swept over a range of values, resulting in a range of output values. The resulting output/input relation is called the static calibration curve for the given set of constant values of the other inputs. the varying input is (one of) the desired measurand(s) and the other inputs are the interfering and system-modifying inputs
  b) It is common practice to limit the number of required measurements by running through the calibration values twice: once in the order of increasing values and once in the order of decreasing values.
  c) We plot the measured values as a function of the calibration values. We draw the best fitting straight line through the measured points. This line is called the calibration curve.

d) It is noteworthy that the slope of the line, a, and the intercept with the ordinate, b, are statistical values, characterized by an average value and a standard deviation.

e) Usually it is assumed that the measured values have a Gaussian distribution. From statistics theory it follows that 99.7% of all observed values are comprised in the interval 3sm, where sm is calculated with standard deviation by the linear regression.

f) 书本 P19

- To use the calibration curve in an actual measurement we proceed as follows.
  a) Assume that we measure a voltage VM1.
  b) With this VM1 a range of corresponding possible real voltage values VW can be identified
  c) The width of the interval for VW is 6sM/a . However, the most probable value for VW is VW1 which according to the calibration curve corresponds with VM1. → with formulas
  d) In practice the accuracy of an instrument is often represented by one number. Very often this number is determined by taking the largest observed deviation between the regression line (= best fitting line) and a single measurement performed during the calibration procedure.
- Accuracy of calculated results: 2 methods.

$$E_a = \left| E u_1 \frac{\partial f}{\partial u_1} \right| + \ldots + \left| E u_n \frac{\partial f}{\partial u_n} \right|$$

$$E_a = \sqrt{(E_{u_i} \frac{\partial f}{\partial u_i})^2 + \ldots + (E_{u_i} \frac{\partial f}{\partial u_i})^2}$$

- Conversion does not improve the accuracy!
- **Non-linearity**
  a) The non-linearity is defined as the maximum deviation between the real transfer function and a perfectly linear function that approximates the sensor behavior in its dynamic range as good as possible
  b) For example it is possible to construct a linear fit by connecting the two extreme points of the real characteristic ('endpoint linearity'). In that case the error due to non-linearity is zero in the two end points and reaches one or more maxima somewhere in between.
  c) In some cases it is desired to have a greater accuracy (linearity) in a certain sub-interval of the dynamic range – fever thermometer.
- Hysteresis 滞后
  With some sensors the output is not an unambiguous function of the immediate value of the physical quantity, but exhibits a hysteresis loop if the value of the measurand increases and decreases. → e.g. due to friction 摩擦
- The amplitude in volts of the noise signal is proportional to the square root of the bandwidth (Hz).

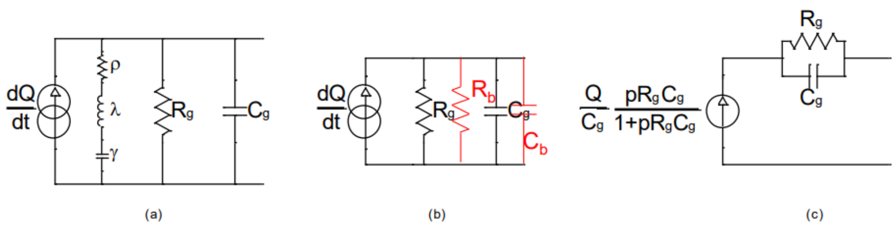
1.7 Dynamic characteristics

- Bandwidth: it is possible to define an inherent bandwidth of a sensor.
  a) each sensor needs a finite reaction time T1 to follow a sudden change of the physical signal (measurand), then revert back to the original value with another time constant T2
  b) The inverse values of the time constants T1 and T2 are the upper respectively lower cut-off frequencies (1/T1 resp. 1/T2) of the sensor and the difference between them is per definition called the inherent bandwidth of the sensor.
- 0^{th} order transfer function

  A zeroth-order sensor immediately reacts to every variation of the measurement. → does not contain any energy-storing elements. S(t)=Am(t)+B
- 1^{st} & 2^{nd} order: A second-order differential equation is needed if the sensor comprises two energy-storing elements (e.g. a mass + a spring, like in an accelerometer). 余略 → bode diagram
- Determining the intrinsic bandwidth of a sensor

  It is sometimes very hard to experimentally determine the intrinsic bandwidth of a sensor, which is a result of the fact that the output signal of the sensor can only be studied by putting the sensor in a measurement chain.

Piezo-electric transducer (e.g. microphone)



- determine $\tau_g = R_gC_g$: tangent to step response
- measuring = loading with R_b and C_b
- measured time constant $\tau_s = R_sC_s$
- $C_s=C_g+C_b$; $R_s=R_g||R_b$ → $R_b << R_g$
- τ_g not found
- Lower cut-off frequency determined by R_b instead of R_g.

in practice, it often happens that the bandwidth of a measurement system is deliberately made smaller than the intrinsic bandwidth of the sensor in order to realize a larger signal/noise ratio.

1.8 Other characteristics 略

Problem Page 80

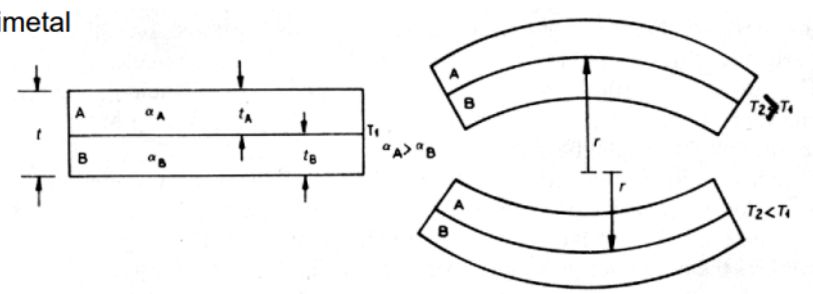
2 Primary sensors 初级传感器

- primary sensors convert a certain physical quantity to another. The term primary sensor is used in particular for those transducers that convert a measurand that is difficult to measure directly to a form that can more easily be measured with a normal sensor.

2.1 Temperature

- A bimetal consists of two metal strips welded onto each other and exhibiting a different thermal coefficient of expansion (TCE). If at a temperature T1, both strips are straight and have the same length, then at a temperature T2<>T1 one strip will become longer than the other, which results in a circular deformation of the bimetal.
- All usable metals enhibit TCEs that are positive. To achieve a good sensitivity, one produces bimetal strips using a metal with a high TCE on one side and a metal with a very small TCE at the other side.

- Bimetal



- radius of curvature $r \cong \dfrac{2t}{3(\alpha_A - \alpha_B)(T_2 - T_1)}$
- Metal with high TCE α + metal with low α (invar)
- MEMS: Si + Al

2.2 Pressure

- Many pressure sensors consist of a primary pressure sensor in combination with a displacement/strain sensor. Measuring pressure either implies comparing the exerted force with a reference force 将施加的力与参考力比较, or measuring its effect on an elastic element. Most primary pressure sensors are based on the elastic deformation of an element with a specially designed shape. Depending on the desired measurement range one chooses another material and/or shape.
- E.g. U-tube manometer (used in cleanrooms).
- E.g. Bourdon tube: a bent or twisted flat metal tube of which one end is closed. Normally one starts from a normal tube with circular cross section, which is plastically deformed until the desired form is obtained. Under the influence of an overpressure that penetrates the tube via the clamped open end, the tube 'tries' to straighten itself. This elastic deformation causes a displacement of the movable other (closed) end, the magnitude of which is a measure for the pressure.
- E.g. a diaphragm: a flexible circular plate which is clamped all around, but bends (deflects) and stretches as a result of the existing pressure difference between the top and the bottom side of the plate. It is clear that a large, pliable and thin membrane (薄膜) will exhibit the largest

deflection. However, a thin membrane is also vulnerable.

- Capsules or bellows: larger displacements, sensitivity for acceleration & shock, poor dynamic behavior and limited range.

2.3 Flow

- A laminar/viscous flow occurs if a fluid flows through a straight, smooth-walled channel with constant section, in such a way that all particles move in the same direction along a trajectory (streamline) parallel to the wall of the channel.
- A turbulent flow is characterized by the occurrence of speed components perpendicular to the walls of the channel, so that only the average speed of all particles is parallel to the axis of the channel.
- Using a orifice plate or diaphragm 使用孔板或隔膜, to measure the pressure difference that emerges between the front and back side of an obstacle 障碍物 that is inserted into the flow, based on the Bernoulli's theorem.

$$p + \rho gh + \frac{\rho v^2}{2} = \text{constant}$$

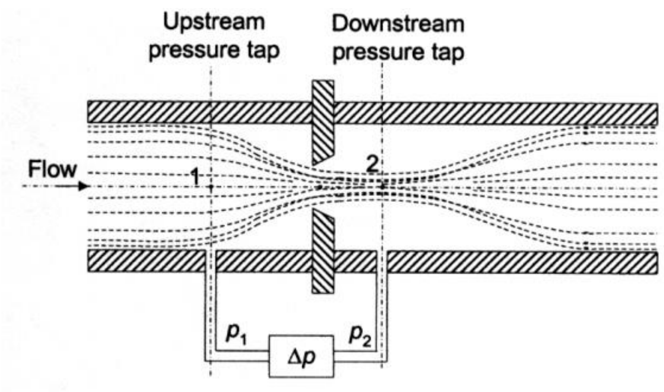


Figure 13 An *orifice* causes a pressure drop that depends on the flow rate.

- **Flow nozzle:** 流量喷嘴 & **Venturi tube** 文丘里管
- They are based on the same principle as the orifice but cause less perturbation of the flow through the tube. The correction factor for the flow rate lies much closer to 1 for these primary flow sensors.
- **Rotameter**: relies on Bernoulli's theorem, but instead of measuring the pressure difference over a certain narrowed cross, the pressure difference is imposed (强加的) and one watches which cross section matches the pressure difference.

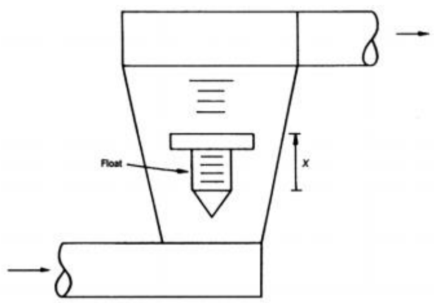


Figure 15 Rotameter: the height of the float indicates the flow rate.

- 文丘里效应：当流体流经收缩管道（如文丘里管）时，流速增加，压力下降。这种效应专门描述了流体在通过管道的收缩和扩张部分时的行为。
- 伯努利效应：这是一个更广泛的概念，描述了流体在流动过程中速度和压力的关系。它适用于任何流动情况，而不仅仅是特定的管道形状。
- **Pitot tube:** 皮托管 A tube with a bend of 90 degrees is put into an open channel with one end pointed against the flow, The other end of the tube is facing vertically up. The fluid penetrates the tube until a certain height is reached. In equilibrium this fluid column will exert just enough pressure to put the incoming fluid to a standstill:

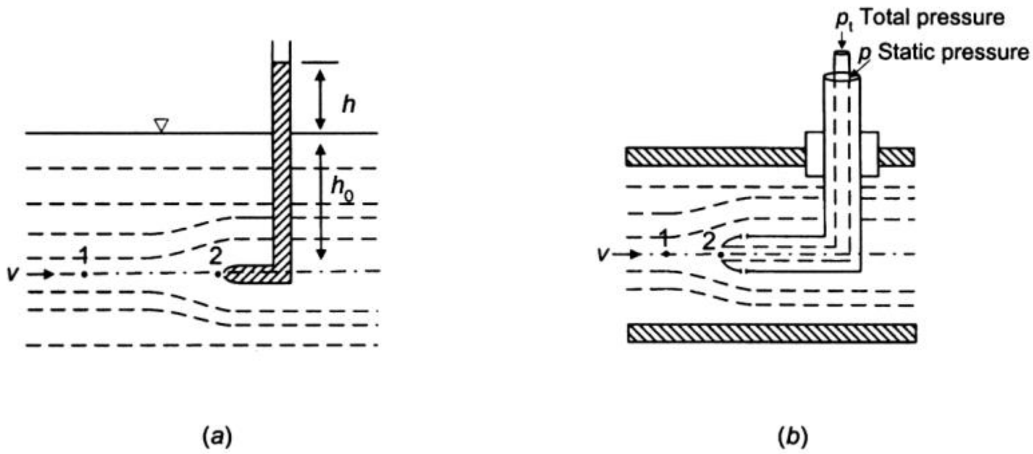


Figure 16 Pitot tube. (a) in an open channel, (b) in a tube

3 Sensor electronics and signal conditioning

- Most sensors do not produce an electric voltage directly but act as passive components, whose value changes under the influence of physical quantity that constitutes 构成 the measurand.
- By means of 通过 an electronic circuit the sensor value can be converted into a voltage. Which in turn can be digitized by an analogue-to-digital converter (ADC). The circuit that is used to convert the passive quantity into a voltage is generally called the sensor electronics.
- In addition to producing a measurable voltage, the sensor electronics can perform other functions, for example the linearization of the voltage as a function of the measurand, or limiting the bandwidth in order to reduce the influence of noise. Such functionalities are called signal conditioning.

3.1 Amplitude modulating signal conditioners

- The simplest example of a signal conditioner in which changes of the impedance of the sensor give rise to changes in the amplitude of the output signal is the voltage divider.

$$V_m = \frac{Z_s}{Z_b + Z_s} V_c$$

4 Discussion of sensors

5 Actuators

Partim 1: SENSA (version 2024):

General philosophy: syllabus = curriculum; slides = illustrations to clarify curriculum, except in a few cases that are mentioned below.

Chapter 1
Completely, except:
Table 1.1: do not learn by heart.
1.8. Other sensor characteristics: do not learn by heart this list
(but do study 1.8.1 until the end of the chapter)

Chapter 2
Completely, except:
Equation (2.3) (deflection of a membrane) do not learn by heart

Chapter 3
Completely
3.3.1 (linearization of sensor): of course not needed to learn the numerical values by heart.
+ do study the alternative method for linearization (presented as an exercise on slide 116)

Chapter 4
Completely
Do not learn by heart equation (4.5)
+ do study: alternative applications PTC (only shown on slides!)
Box with Liga technology (p 98): illustration only.
Equations (4.91) and (4.92) (LVDT, 'One can prove that'): do not learn by heart.

Chapter 5
Completely

Slides
I have uploaded to Ufora a file with all slides so you do not have to work with multiple files. Study all slides, except:
1-11, 23-24, 29, 47: only illustration; 48: only what was said about the circled fields.
99 (pitot tube airplane): do not learn by heart this formula
104: only illustration
132: figure thermostat: do not study this figure in detail
154: illustration only
191, 204, 210: illustration

Also all little exercises! (solutions: see Ufora, unless the solution was presented during a lecture)