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ME3003

# **Introduction to Flow Sensors and Datasheet Reading**

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HCMC, November 16, 2020

# Abstract

Data acquisition is one of the crucial steps of designing a mechatronic system. Changes in the environment must be observed for decision making purposes.

Sensors can be seen anywhere such as natural or man-made objects. The natural sensors, like those found in living organisms, usually respond with signals having electrochemical character. In man-made devices, information is also transmitted and process in electrical form. Application for sensors is almost limitless, from simple system such as car door monitoring arrangement to extremely complex one like Mars Exploration Rover – B.

Since the topic about sensors is so vast and technical, designing a complex sensor is beyond the scope of this report. Therefore, in our project, we only focus on flow sensor, and specifically how to make the best of the sensor catalog. This goal includes what parameters are important in choosing the right flow sensor for one's project, expected failure modes during operation and maintenance of the sensor, which makes the report somewhat practical in designing the system as a whole.

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# Chapter 1

## Characteristics of a sensor

When designing a mechatronic system, sensor is crucial for data acquisition and generating an adequate response. However, if an engineer only relies on the best available sensor, the product price will be higher than necessary, resulting in customers lost to competitive manufacturers. Therefore, this chapter is dedicated to accommodate selecting the right sensor for one's application with common characteristics available on datasheets.

### 1.1 Mobile Communication Devices



Figure 1.1: Built-in sensors in a typical present-day smartphone

Mobile Communication Devices (MCD) sensors are designed for portability and full integration with other components inside a hand-held device. It is a self-containing sensing module that detects, conditions, digitizes, processes, outputs and communicates information while being small, light, accurate, stable, fast-response, etc. A generic purpose device (e.g. smartphones, tablets, smartwatches) contains dozens of them for different applications and is categorized in 4 areas:

1. **Industrial** for detecting noncontact temperature, thermal imaging, humidity, air flow ionizing radiation, smell, dielectric constant of objects, material composition, range (distance), air pressure, produce freshness, etc.
2. **Medical** for the inner (core) and skin body temperatures, thermal imaging, arterial blood pressure, EKG, blood factors (glucose, cholesterol, hemoglobin oxygen saturation), deep body imaging, smell (e-nose), behavior modification, etc.
3. **Military** for night vision, detecting poisonous gases, proximity, ionizing radiation, explosives, chemical and biological agents, etc.

4. **Consumer** for the body core temperature, heart rate, radon gas, pregnancy detection, breathalyzer for alcohol and hydrogen sulfide, food composition, behavior modification, proximity, V level, electromagnetic pollution, surface temperature, etc.

## 1.2 Full-Scale Input/Output

A *span* or an *input full scale* (FS) is a dynamic range of stimuli convertible by a sensor. In a datasheet, it is regarded as the highest possible input value without causing unacceptably large error. For sensors with broad response characteristics, the span is often expressed in decibels, which is a logarithmic measure of ratios of either power or force (voltage).

A *full-scale output* (FSO) for an analog output is the difference between electrical output signals at 2 ends of the input signals. For digital output, it is the maximum digital count the A/D converter can resolve for maximum FS.

## 1.3 Accuracy

It is defined as *maximum*, or *typical*, or *average* error of the sensor alone. The rating of accuracy is represented in 4 common forms, depending on the application:

1. *Directly in terms of measured value of a stimulus*, which is used when error is independent on the input signal magnitude.
2. *In percentage of FS*, which is useful for a sensor with a linear transfer function and can be thought as an alternative of the approach above. For nonlinear transfer function, the representation may be misleading.
3. *In percentage of the measured signal*, which is useful for a nonlinear transfer function, even with very dynamic inputs. However, the error typically does not proportionally scale with the input magnitude.
4. *In terms of the output signal*, which is useful for sensors with a digital output format.

In reality, a datasheet mixes 2 or more forms and take whichever value is the largest. In this way, the error can be evaluated more accurately.

## 1.4 Possible types of error

In a datasheet, tolerance and error limit are paramount for any measuring equipment, which the manufacture always dedicates a section for. Distinguishing the types of error is helpful to determine the suitable sensor for designing a mechatronic system. Generally, there are 6 types of error:

**Calibration error** Calibration error occurs while adjusting a sensor. In dynamic system and control, it is categorized as *disturbance*, which is quantitative data and contributes the systematic error. Another source of errors regarding calibration is a reference sensor. This type of sensor is considered as national standard, which all manufactured sensors rely on. Therefore, for absolute accuracy, the error from "standardized sensors" is considered.

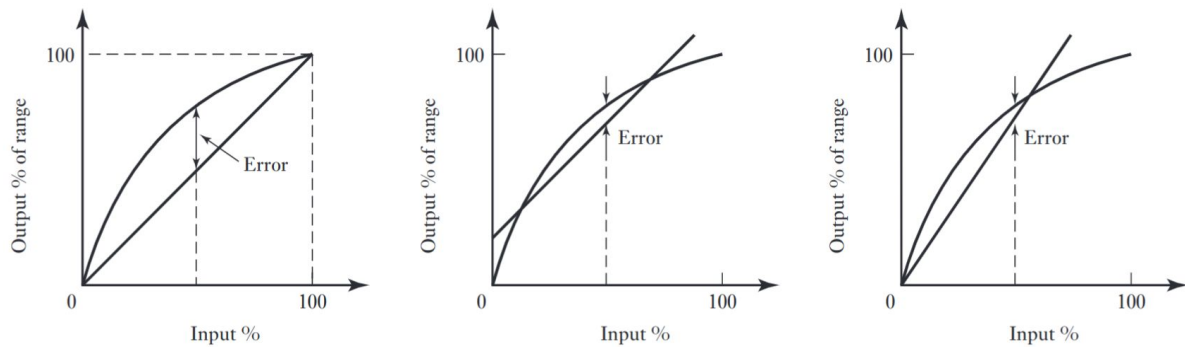


Figure 1.2: Non-linearity error using (from left to right): end-range values; best straight line for all values; best straight line through the zero point [1]

**Hysteresis error** Hysteresis error is the maximum deviation between output values given the same input signal. For example, if the sensitivity of the sensor is 10 mV/mm, the hysteresis error in terms of displacement units is 2 mm. Possible causes of this faulty result are geometry of design, friction or deformation of material.

**Nonlinearity error** If the error is assumed to , nonlinearity error will be specified to compensate for any faulty assumptions. It is the maximum deviation of a real transfer function from the approximation straight line. After several calibration runs, the worst linearity result is stated. This type of error is crucial if the output signal requires best accuracy in a small range (e.g. medical thermometer measures body temperature between 36 – 38°C). Oftentimes, manufacturers are inclined to publish the smallest possible nonlinearity error without specifying what approximation method is used.

**Saturation error** Saturation error occurs when the input signal exceeds the operating limit of a sensor.

**Repeatability error** Repeatability error causes a sensor to output different values under identical conditions. Possible noises for the error are thermal conductivity, charge, deformation, etc.

**Dead band error** Dead band error is the insensitivity of a sensor in a specific range of the input signals, which generates output signals between a certain value (often zero).

## 1.5 Resolution

Digital input-output signals are not continuous as shown in the figures in a datasheet but rather distinguish data points. The distance between 2 consecutive data points is defined as resolution. Depending on manufacturers, the step size may be specified as typical, average, or worst.

## 1.6 Special output characteristics

Depending on sensor types, specifying input properties might be necessary. For instance, in case of flow sensors, thermal transport sensors require identifying temperature bandwidth to give the accurate response.

**Impedance** When working with an electronic sensor, the output impedance of the sensor  $Z_{out}$  and the input impedance of the connecting system  $Z_{in}$  should be acknowledge. A current generating sensor should have high  $Z_{out}$  and low  $Z_{in}$ . This is the opposite for voltage generating sensor.

**Format** For mechatronic systems, programming a microcontroller or microprocessor needs the output format of the sensor. The output electrical characteristics may include voltage, current, charge, frequency, amplitude, phase, polarity, shape of a signal, time delay and digital code. These responses can be displayed in formats such as binary, text (ASCII), or digital output, etc. with various forms of communication (e.g. serial link, PWM,  $I^2C$ ).

**Excitation** Analogues to a match catching fire with a spark, excitation signal could be included in a datasheet. An example of an excitation signal is electric current passing through a thermistor to measure its temperature-dependent resistance.

**Dynamic characteristics** Besides from steady input signals, dynamic and time-varying stimuli are also considered. The sensor responses slowly to this input type, which generates dynamic error. At best, the error is a delay. At worst, it causes undesirable oscillations. In such cases, Dynamic Systems and Control course is provided to discuss extensively about this topic.

## 1.7 Environmental factors

Generally, all possible environmental factors that may affect the sensor performance are specified by manufacturers. In a datasheet, it is typical to include information about the following factors:

1. *Storage condition*, which specifies the highest and lowest storage temperature. It also has maximum relative humidities at these temperatures and may be mentioned as "noncondensing". Along with operating temperature range, this information is *one of the most common environmental factors* available in any datasheet.
2. *Short-term stability* is manifested as changes in the sensor's performance within minutes, hours, or days, which essentially is another way to express bidirectional repeatability.
3. *Long-term stability* is the irreversible change in the material's electrical, mechanical, chemical or thermal properties. Similar to heat treated materials, a sensor can improve its stability by *pre-aging*. For instance, a sensor may be periodically swung from freezing to hot temperatures before being calibrated and installed into a product.
4. *Environmental conditions during normal operation* affects the transfer function of a sensor. An example is a strain gauge whose sensitivity increases with temperature. Even if the manufacture does not specify these conditions in the datasheet, it is the responsibility of an engineer to simulate and prototype the end-product corresponding to the environment.



## 1.8 Reliability

In statistical terms, reliability is the probability that the device will function without failure over a specified time or a number of uses. Reliability specifies a failure is a temporary or permanent malfunction of a device. Although this is an important property of a sensor, the information is not readily available in most datasheet due to the absence of measuring standards of reliability. Therefore, an engineer should be ready to do the test by any means. Some example testing procedures are MTBF, extreme testing, accelerated life testing, HALT testing, FOAT testing, etc.

## 1.9 Application characteristics

This information includes geometry and other simple physical specifications such as design, weight, power consumption and overall dimensions. Although price heavily influences a sensor's performance, any amount of cost is justified if reliability and accuracy are of a paramount importance.

## 1.10 Uncertainty

While error is what we unknowably get when we measure, uncertainty is what we think how large that error might be. No matter how well a sensor is made, there always exists obscure factors. Even if they are recognized, it is impossible to measure exactly (e.g. human factor). Attempts have been made to quantitatively identify them: evaluation through statistical methods, preceding measurement data, personal experience, manufacturer's specifications, uncertainty data referenced from handbooks and manuals, etc.

# Chapter 2

## Introduction

### 2.1 Characteristics of a flow sensor

There are 2 types of moving media [2]:

- liquids. *Ex:* water, oil, gasoline.
- air and gas. *Ex:* O<sub>2</sub>, N<sub>2</sub>, CO<sub>2</sub>, CH<sub>4</sub>.

Although flow sensors may be simple as detecting velocity of the fluid or air/gas,

### 2.2 Several examples of flow sensors

#### 2.2.1 Pressure gradient technique

This technique is applicable only for measuring **steady flow of nonviscous, incompressible medium** using Bernoulli equation, which relates to *flow resistance*. The working principle of this technique is as follows:

1. Create a medium impeding the flow motion in a section of the pipe, such as orifices, porous plugs, and Venturi tubes.
2. Place 1 differential pressure sensor between the normal sections or 2 absolute pressure sensors in each normal section of the pipe.
3. Because the high resistance area creates a slight pressure difference in the flow, the mass transferred through the pipe can be estimated.

The equation for finding mass flow is:

$$q = \epsilon A_2 \sqrt{\Delta p} \quad (2.1)$$

where

- $q$  is the mass flow per unit time, kg/s.
- $\epsilon$  is the calibration coefficient.
- $A_2$  is the cross section of the high resistance area, m<sup>2</sup>.

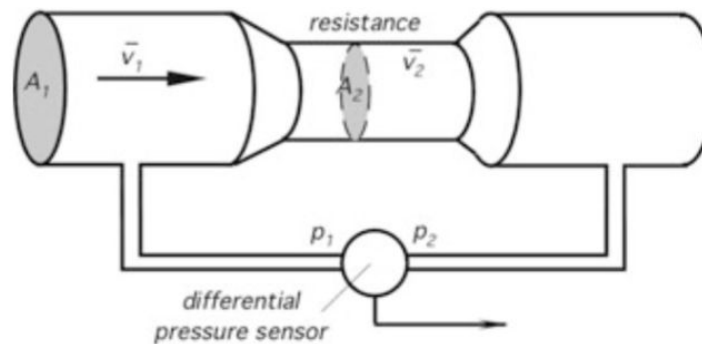


Figure 2.1: Pressure gradient technique example using narrow channel flow [2]

- $\Delta p$  is the pressure difference, Pa.

Derivation of the equation is provided in chapter 12 [2].

Advantage of the pressure gradient method is in the absence of moving components and use of standard pressure sensors that are readily available. A disadvantage is in the restriction of flow by a resistive device.

### 2.2.2 Thermal transport sensors

Thermal transport sensors work by "marking" the flowing medium and detecting the movement of the mark. They are also called *thermoanemometers*. Thermoanemometers are sensitive and have a broad dynamic range. Since the "mark" moves, no moving component is required and low flow rates can also be measured, unlike pressure differential sensors. Another benefit is detection of material change in composition.

A thermoanemometer design determines its operating limit. The upper limit of FSO is determined experimentally.

Data processing system for thermoanemometers must receive at least 3 variable input signals: a flowing medium temperature, a differential, a heating power signal. The signals are multiplexed (i.e. MISO operation), converted into digital form, and processed by a computer to calculate characteristics of flow, displayed in velocities, volume rates or mass rate

#### Hot-wire/hot-film Anemometers

It is a single-part sensor. The wire resistance typically is  $2 - 3 \Omega$ . The operating principle is based on warming up the wire by electric current to  $200 - 300^\circ\text{C}$ . No media temperature compensation is required. As the flow moves through the wire, it reduces the temperature of the hot wire. The faster the media flows, the stronger the cooling. This phenomena is also known as *forced convection*.

There are 2 methods of controlling temperature and measuring a cooling effect: constant voltage and constant temperature.

- Constant voltage: reduction in the wire temperature is measured while the voltage between 2 ends of the wire is constant.
- Constant temperature: the temperature remains constant. The power feeds to the wire compensates for temperature loss.

The compensating voltage  $\delta V$  for a small change in resistance  $R_w$  is:

$$\delta V = V_{out} \left( \frac{R_w + \delta R_w}{R_w + \delta R_w + R_1} - \frac{R_w}{R_w + R_1} \right) \approx V_{out} \frac{\delta R_w}{R_w + R_1}$$

Then, relation between  $R_w$  and temperature change of the hot wire is obtained through experiments and in-depth research regarding the topic. Typical design of the hot-wire sensor is shown

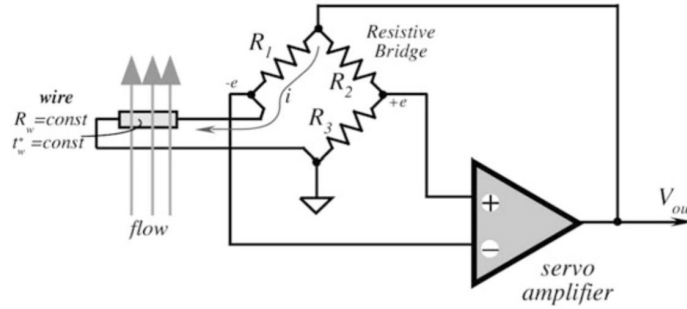


Figure 2.2: Null-balanced bridge for a constant temperature hot-wire anemometer [2]

in **Figure 2.3**. Common materials for the wires are:

- tungsten. The wires are strong and have high temperature coefficient ( $0.004^\circ\text{C}^{-1}$ ). However, they are prone to high temperatures in many gases due to poor oxidation resistance. This is the most common material at present.
- platinum. The wires have high oxidation resistance and temperature coefficient ( $0.003^\circ\text{C}^{-1}$ ). However, they are weak, especially at high temperatures.
- Platinum-iridium alloy. The wires have good oxidation resistance and are more durable than platinum. However, they have low temperature coefficient ( $0.00085^\circ\text{C}^{-1}$ )

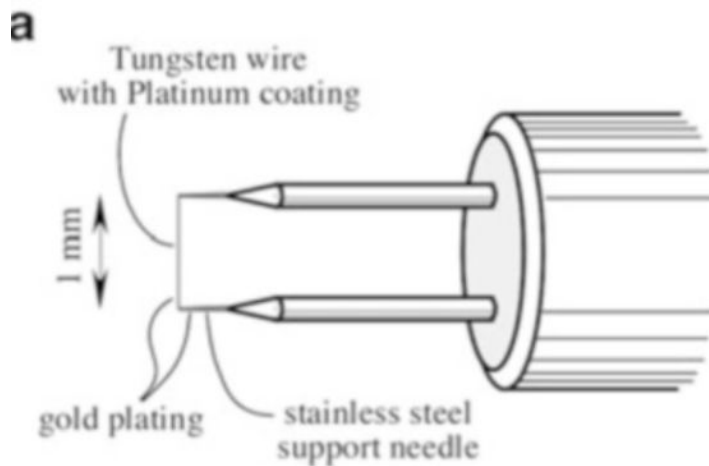


Figure 2.3: Hot-wire probe typical design [2]

Typical design of hot-film sensor is shown in **Figure 2.4**. A common material for the film layer is platinum. The insulator could be made of ceramic substrate.

The hot-film sensor has several advantages over hot-wire sensor:

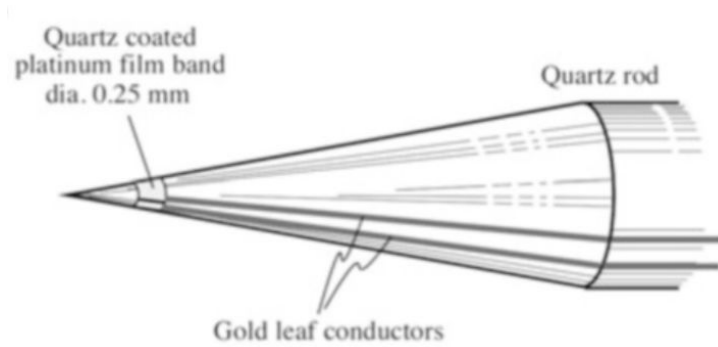


Figure 2.4: Hot-film probe with cone-shaped design [2]

- Better frequency response due to large surface area with the same rod diameter.
- Lower heat conduction to the supports due to low thermal conductivity of the substrate material.
- More flexible configurations (e.g. wedge, conical, parabolic shapes).
- Less susceptible to fouling and easier to clean.

### Three-part Thermoanemometer

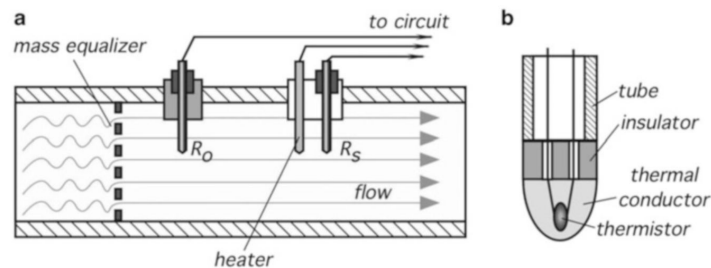


Figure 2.5: Schematic representation and cross-sectional view of a three-part thermoanemometer [2]

This type of thermoanemometer is used primarily for liquids but can also be used for gases. The design makes it resistant to contaminated environments. The temperature detector  $R_o$  measures the current temperature of the flowing medium. The heater then warms up the medium and the elevated temperature is measured by the second temperature detector  $R_s$ . Through convection phenomena, the amount of heat dissipation is converted to the flow rate of the medium. However, laminar flow must be obtained before measurements for accurate result.

In industry and scientific measurements, resistance temperature detectors (RTDs) is preferable for higher linearity, predictable response and long-term stability over a broader temperature range.

In medicine, thermistors are often preferred for higher sensitivity.

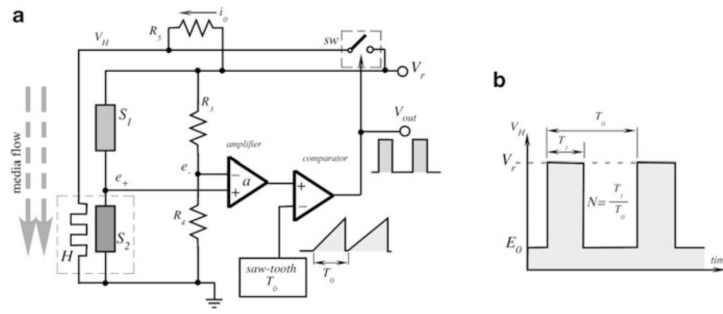


Figure 2.6: Control circuit of a thermoanemometer with PWM modulator [2]

### Two-part Thermoanemometer

Fast-response sensors like hot-wire and hot-film sensors are expensive and delicate. More robust and resistant sensors without need of responsiveness (about 0.5 s) requires different design approaches. The working principle of two-part thermoanemometers is similar to three-part thermoanemometer: measuring temperature of the flowing media; heating the media; monitoring the cooling effect caused by the flow. However, the heat and the second temperature sensor are combined into one sensor.

The thermoanemometer works by a control circuit with a Wheatstone bridge. It generates an output PWM signal where the duty cycle  $N$  represents the airflow rate.

Another thermoanemometer used in precise semiconductor manufacturing is microflow thermal transport sensors. This sensor is developed with MEMS technology. This topic is very advanced and beyond the scope of this report.

### 2.2.3 Ultrasonic Sensors

The working principle of the sensor can be categorized in 2 ways:

- detection of frequency. It uses Doppler effect.
- phase shift caused by flowing medium. It relies on the detection of the increase or decrease in effective ultrasound velocity in the medium.

To use the sensor, it is desirable to calibrate the ultrasonic sensors with actual fluids over the useful temperature range so that contribution of a fluid viscosity is accounted for.

### 2.2.4 Electromagnetic Sensors

The electromagnetic flow sensors are useful for measuring the movement of conductive liquids. The operating principle is based on the discovery of Faraday and Henry of the electromagnetic induction. The voltage is induced with an alternating magnetic field. The frequency of magnetic field must be at least 2 times higher than the highest frequency of flow rate variations (Nyquist frequency). This value is typically around 100 – 1000 Hz.

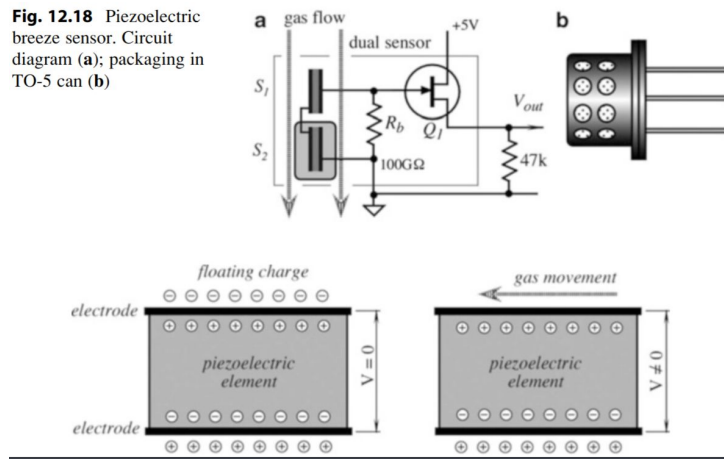
### 2.2.5 Breeze Sensors

Breeze sensors are used when detection of change in the air/gas movement is needed but not its instantaneous velocity. Gas movement strips off electric charges from surface of piezoelectric



Figure 2.7: Electromagnetic sensors MC162

**Fig. 12.18** Piezoelectric breeze sensor. Circuit diagram (a); packaging in TO-5 can (b)



element. The voltage induced by piezoelectricity phenomena is applied to the JFET follower creates an output signal at the terminal.

### 2.2.6 Coriolis Mass Flow Sensors

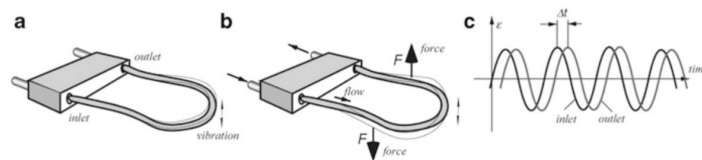


Figure 2.8: Coriolis sensor's working principle. The phase shift relates to the mass flow

The sensors measure flow of mass directly. Since they are essentially unaffected by the fluid pressure, temperature, viscosity and density, the sensors can be used without recalibration and without compensating for parameters specific to a particular type of fluid. Moreover, gas applications can benefit greatly with these sensors. The Coriolis force is calculated using the following equation:

$$F = 2m\omega v$$

where  $m$  is the mass,  $\omega$  is the rotation speed,  $v$  is the vector of the average fluid velocity. The design of this sensor is shown in **Figure 2.8**. Although having many great advantages, the cost of the sensor is high (about 60,000,000 VND). Therefore, depending on application types (such as measuring multiple fluids), the usage value can offset the initial price.



Figure 2.9: Coriolis mass flow sensor

### 2.2.7 Drag Force Flowmeter

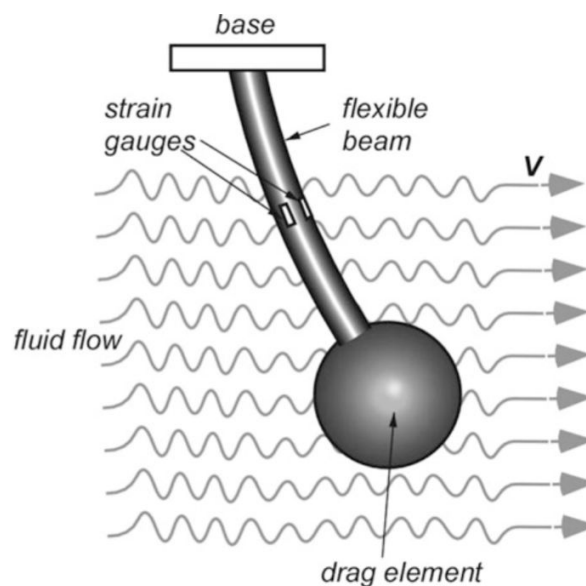


Figure 2.10: Schematic of the drag force sensor

For sporadic, multi-directional, turbulent fluids, a drag force flow is efficient. However, it requires environmental monitoring, meteorology, hydrology, maritime studies to measure speeds



of air or water flow and turbulence close to surface. The force exerted by the fluid on the drag element is measured (strain measurement of deformation) and converted to an electrical signal indicative of a value for flow speed. This approach can measure 3 dimensional flow instead of 1 dimension like other sensors. A variation of this sensor using MEMS technology is cantilever MEMS sensors, which is again, beyond the scope of the report.

### 2.2.8 Dust and Smoke Detectors

Although airflow is not monitored, their operation requires movement of gases through the detection chamber of the sensor. To detect presence of small particles suspended in the air, there are 2 types of sensors widely employed: ionization and optical detectors.

#### Ionization Detectors

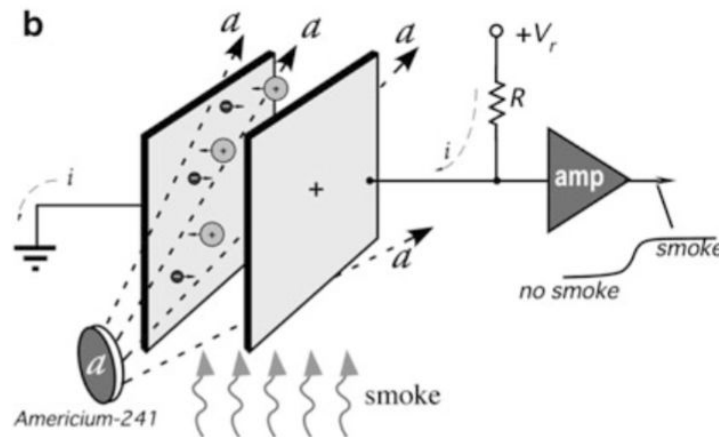


Figure 2.11: Schematic representation of ionization process in smoke detectors

An ionization chamber containing Americium-241. The radioactive isotope produces alpha particles with a half-life of 432.2 years. If no smoke goes through the space between 2 plates, the alpha particles emanated by Americium-241 ionizes the air molecules by breaking them into positively charged ions and negatively charged electrons. This creates a small current or "virtual wire" for the voltage source  $V_r$  goes to the ground on the left side plate.

If smoke goes through the space between 2 plates, the alpha particles can no longer ionize the air molecules inside the chamber, thus cutting off the "virtual wire". The voltage source then goes through the amplifier "amp", indicating that smoke exists in the room.

#### Optical Detectors

The effect is the same with optical detectors. If the light source is obstructed from the detector by the smoke, it signals that there is smoke inside the room. However, distinguishing the light coming from the emitter and ambient light with the scattered light from the smoke is the main problem. A possible design is illustrated in **Figure 2.12**. Depending on the designer's implementation, each smoke detector will have different positioning schemes.

For responding to the light pulses resulted from larger particles, the electronic interface circuit should have a sufficiently wide frequency bandwidth. The optical smoke detectors are

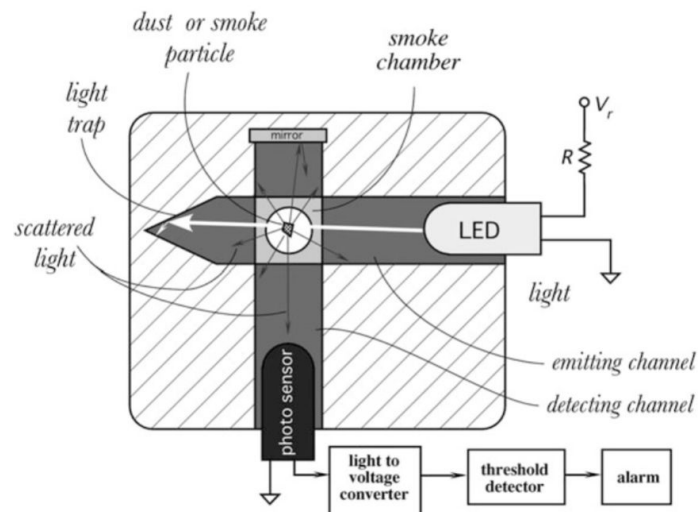


Figure 2.12: Cross section of an optical smoke detector. The photosensor and LED could be crossed at less than 90 degree at the expense of mechanical complexity [2]

less prone to false alarm resulted from steam or cooking fumes in kitchen than the ionization smoke alarms

## **Chapter 3**

### **Summary and Conclusions**

In summary, the report introduces a general list of considerations before deciding to buy a sensor. It also introduces a number of flow sensors available in the market. Since the author's knowledge regarding sensor technology is poor, the report is only limited to studying working principles of simple sensors. However, what is more desired for university students is to acknowledge and appreciate the design of many existing sensors. In addition, knowing how to read datasheets and implement the sensor in designing mechatronic systems is extremely crucial, which is the initial goal of this project.

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