

Micro Robotics

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Week-7

Lecture-33

Micro Sensors and Micro Transducers - Module 08

Here we are focusing on the micro sensors and micro transducers for micro robotic systems. We had discussed the gyroscopic accelerometers, the different configurations of gyroscopic accelerometers, and the mechanical switches. Here, we will discuss the flow transducers. The flow transducer is a device that converts one form of energy into another form. These flow transducers are specialized transducers that measure and monitor the flow rate of the fluid and convert the information into an appropriate electrical signal. Some of the key importance of the flow transducers in micro-robotics is mainly for precision measurements.

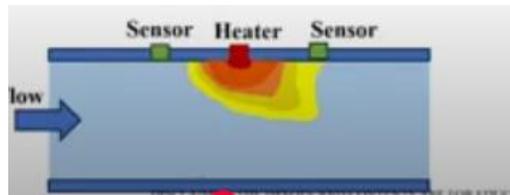
It enables accurate monitoring of minute fluid movement in a microscale environment. It gives us real-time data and provides instant feedback for microrobot navigation and control. It is applicable in various microfluidic systems and environments. From an integration perspective, it facilitates the development of smart, responsive micro-robotic systems.

Some of the key components of these flow transducers include the sensing elements, which detect the changes in the fluid flow, examples like thermal sensors, pressure differential sensors, ultrasonic emitters and receivers, etc. Now, with reference to the transduction element, it converts flow information into electrical signals. It may involve various principles like piezoelectric, electromagnetic, capacitive, etc. With reference to a functional perspective, it measures the flow rate, the velocity, or the volume of fluid passing through a specific point, and it provides continuous real-time data on the fluid movement. So, these are some of the key aspects regarding the flow transducers.

Now, with a feature perspective, it has very distinct distinguishing features. It is a high precision in measuring small-scale fluid movements, as we have been discussing magnetic-based micro robots or the electrostatic-based micro robots. In all these cases, there is a need

to measure a kind of micro displacement in these particular systems in order to measure these micro displacements in a particular domain. So these flow transducers should be capable enough to have high precision in measuring small scales, and they should have the ability to function in a microfluidic environment, as well as integration capability with respect to microelectronic systems. From an output perspective, it typically produces an analog or a digital electrical signal. The signal amplitude and frequency are often proportional to the flow rate. From an application point of view in micro robotics, it has more scope for navigation and fluid environments. It has precise fluid handling in lab-on-chip devices. Monitoring and control in a microfluidic system are one of the key applications of these micro-robotic systems. Now, discuss the energy conversion mechanism.

With reference to the energy conversion mechanism, the flow transducer converts the physical force of the fluid flow into an electrical signal. This conversion allows for easier handling, transmission, and measurement of flow data. In measurement methods, the thermo-transfer method is crucial. The thermo-transfer method uses heat transfer to measure fluid velocity. It employs a heating element and thermal sensors to detect the energy absorption by the fluid.



Next, with reference to the time-of-flight method, it measures the time taken for ultrasonic pulses to travel between the transducers. It also calculates the flow velocity based on different end transit times. There is one more configuration, which is called the magnetic inductive principle. This magnetic inductive principle utilizes Faraday's law of electromagnetic induction. A conductive medium flowing through a magnetic field generates a voltage proportional to the flow velocity, which is represented by the magnetic inductive principle. Next is called the vortex principle. In the vortex principle, it detects the vortices generated by the fluid flow passing by a bluff body. There are a number of vortices that correlate with the flow rate. Based on real-time monitoring, it provides continuous and instantaneous data on flow rate, pressure, and temperature, and it enables process optimization and early identification of the systems. It facilitates remote monitoring and control through integration with the IoT platform.

The next important aspect is with reference to the signal processing. In signal processing, it has advanced electronics and microprocessor processing with reference to raw flow data. It converts the measurements into a readable format for the operators. By employing these principles, a flow transducer offers accurate real-time flow measurement across various industrial applications, enhancing efficiency and controlling the fluid management systems. Now, when we closely observe the role of a flow transducer in a micro robotic system, one of the key roles includes navigation and sensing for fluid environment mapping. This fluid environment mapping enables the micro-robot to detect and navigate through the complex fluidic channels as well as networks. So either it might be blood flow, or it might be a kind of ocean flow, or sometimes it might be a kind of small lubricant where flow needs to be analyzed. So these should be quite capable. Next is obstacle detection. With reference to obstacle detection, it will help identify the obstruction or changes in fluid dynamics for safer navigation.

The most important point is precision control. In the case of precision control, it involves accurate fluid manipulation. It allows for precise control of fluid flow in microfluidic devices and lab-on-chip systems. It has a feedback mechanism that provides real-time data for adjusting the micro-robot's movement and orientation. With reference to the micro reactor system, flow rate monitoring ensures optimal conditions for chemical reaction and synthesis at a micro scale. Concerning process optimization, it enables fine-tuning of fluid dynamics for improved efficiency and yield. Now, with reference to the biomedical perspective, it is highly used for in vivo sensing. It facilitates the measurement of blood flow or other bodily fluids in an invasive procedure. So, with reference to the drug delivery perspective, it enables precise control of medication release in a targeted drug delivery system. From the environmental monitoring perspective, it has pollutant detection.

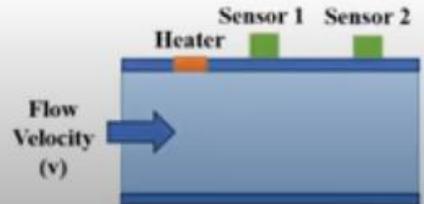
It allows the micro robot to sense and quantify contaminants in the fluid environment. From a water quality assessment point of view, it provides data on flow characteristics in the water treatment process. From a performance enhancement perspective, we have the energy efficiency. The optimized micro-robot movement to reduce power consumption in the fluid environment is one of the major aspects that need to be taken into consideration. With reference to adaptive power, adaptive behavior enables the micro robot to adjust its strategies based on the local flow conditions. Now let us discuss the thermo transfer method. The thermo-transfer method relies on the principle of heat transfer to determine how fast a fluid is moving through a channel. The thermo transfer method operates by utilizing a heated sensor element placed in the fluid flow. As the fluid moves past this heater, it absorbs heat. So, the temperature difference between the heated sensor and the reference sensor measures the ambient fluid temperature.

The greater the flow rate, the more heat is carried away from the heated sensor, resulting in a large amount of temperature difference. So ideally, this will be a heater location, and the sensor will be placed appropriately. This will be helpful in measuring the reference and the output, as well as the influence of the heater on the flow. As far as the measurement process is concerned, a heating element, which is a residue-type temperature detector, acts as a heating element. It maintains a constant temperature above that of the surrounding fluid, and two temperature sensors are used: one for measuring the temperature of the heated element and another for measuring the temperature of the surrounding fluid. So here, the residue temperature heaters/detectors can also be used. However, in certain cases, these resistance temperature detectors can act as sensors themselves. Now, with reference to flow rate calculation, the flow rate can be determined by analyzing the temperature difference ΔT between these two sensors. As the velocity increases, the heat transfer increases, leading to a measurable change, which is considered ΔT . Next, we will discuss the time-of-flight method.

- **Velocity Calculation:** Flow velocity (v) is calculated using the formula:

$$v = \frac{L}{\Delta t}$$

where L is the distance between sensors.



In the time-of-flight method, it is mainly meant to measure the time taken for a signal. It is ideal for thermal or acoustic signals to travel between two points in a flowing fluid. The flow velocity affects this travel time, allowing for accurate flow calculations. The time-of-flight method is classified into two categories. One is called a thermal-based time of flight, and the other is an ultrasonic-based time of flight.

The working mechanism of a thermal-based time-of-flight process, the heat pulse generation, is that a heat ray element creates a brief temperature mark in the fluid. When we consider the downstream detection, the two temperature sensors that are positioned are used for measuring the downstream at a known distance and detecting the passing of this thermal mark. In time measurement, the time difference Δt between the mark reduction at each sensor is measured. In order to calculate the velocity, a flow velocity V is calculated using the equation L divided by Δt . So, L is the distance between the sensors. Now, when we observe the working mechanism, which is like a configuration called the ultrasonic time of flight method. In the case of the ultrasonic time-of-flight mechanism method, the

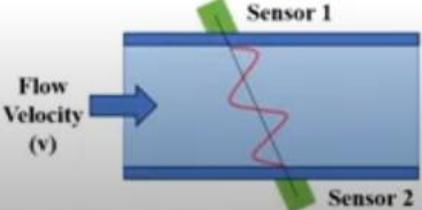
working mechanism is discussed. So there is sensor 1, which is at one particular portion, and the signal from the sensor is collected by sensor 2. Now this ultrasonic transducer emits sound pulses for both upstream and downstream. So when we try to calculate the transit time measurement, the system measures the time taken for a pulse to travel in both directions.

As far as the time difference calculation is concerned, the difference in transit time Δt between the upstream and the downstream pulse is determined. As far as flow velocity calculation is concerned. The flow velocity v is calculated using the formula v equals l divided by t multiplied by Δt , t_{up} and t_{down} . So, t_{up} is the transit time for the upstream, t_{down} is the transit time for the downstream, l is the distance between the transducers, v is the velocity of the system, and Δt is the difference in the transit times. Now, let us discuss the next configuration, which is called a magnetic inductive principle configuration.

- **Flow Velocity Calculation:** The flow velocity (v) is calculated using the formula:

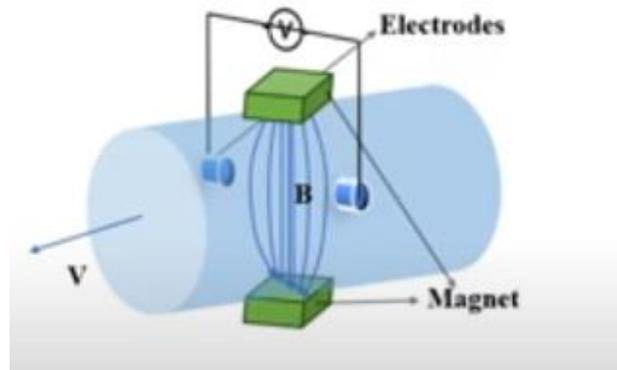
$$v = \frac{L}{2} \times \frac{\Delta t}{t_{up} \times t_{down}}$$

Where:
 L is the distance between transducers
 t_{up} is the upstream transit time
 t_{down} is the downstream transit time

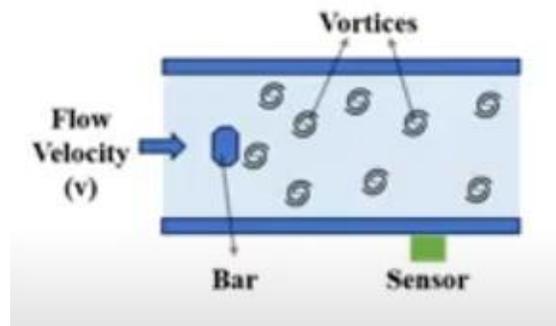


In this magnetic inductive principle configuration, the key components are two electrodes and a magnetic field, and the fluid is moving at the velocity v . So, the key components involved are the magnetic field generated by the coils, the conductive fluid flowing through the pipe, and the electrodes to measure the induced voltage. From the working principle point of view, a magnetic field is created perpendicular to the flow direction. As the conductive fluid flows through this magnetic field, it acts as a moving conductor. This movement induces a voltage across the fluid that is perpendicular to both the magnetic field and the flow direction.

This induced voltage is measured by the electrodes placed on the opposite side of the pipe, and the voltage is directly proportional to the complete flow velocity. Now, when we try to mathematically represent this, the relationship is expressed as E , the induced voltage; B , the magnetic field strength; V , the average flow velocity; and D , the diameter of the pipe. So, E is proportional to BVD . B is the magnetic field strength, V is the average flow velocity, and D is the diameter of the pipe. Now let us take the next configuration called the vortex principle.

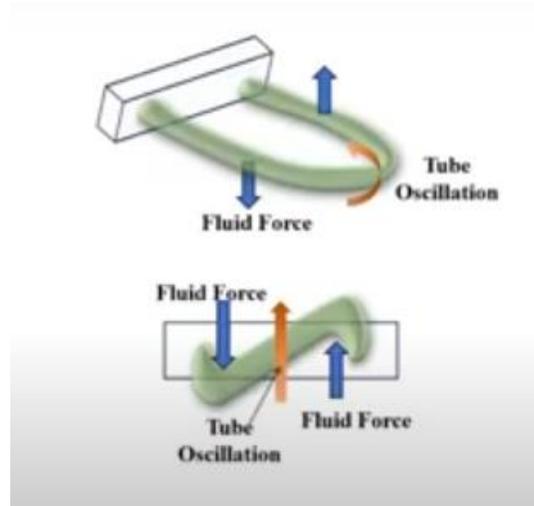


So, in vortex flow-based measurements, the techniques are based on the principle of vortex shedding. The key components involved in this are the bluff body, a specially shaped obstruction placed in the flow path. From a sensor point of view, typically, a piezoelectric or capacitive sensor detects the vortex-induced vibration. From a signal processing point of view, it converts the sensor data into a flow rate measurement. From the perspective of the working principle, it has a vortex formation. As the fluid velocity reaches a critical point, the vortices behind the bluff body alternate from one side to the other of the bluff body. From a pressure fluctuation perspective, the vortices create alternating zones of positive and negative pressures, and these pressure changes occur at a frequency proportional to the flow rate. With reference to the detection perspective, the sensor detects the pressure fluctuations or vibrations caused by the vortices. This generates an electrical signal with a frequency matching the vortex formation rate. With reference to the signal processing point of view, the signal processor analyzes the frequency of the electrical signal using a known relationship, and it converts this frequency into flow rate measurements.



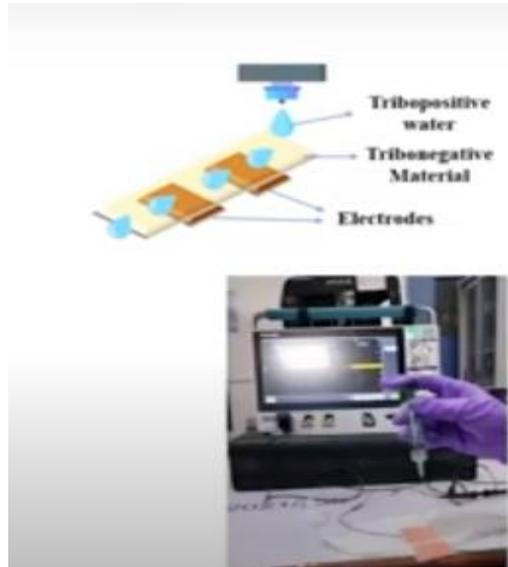
The next configuration is called a Coriolis flow configuration. The Coriolis flow sensors are advanced devices used to measure the mass flow rate, density, and temperature of the

fluid with high accuracy. This sensor operation is based on the Coriolis effect, and it provides direct mass flow measurements without the need for additional calculations. Some of the key components of these Coriolis flow sensors include a U-shaped or straight flow tube, magnetic and coil sensors, and the electronics unit for signal processing. So based on the requirement, so we can appropriately change the configuration of this Coriolis flow sensor.

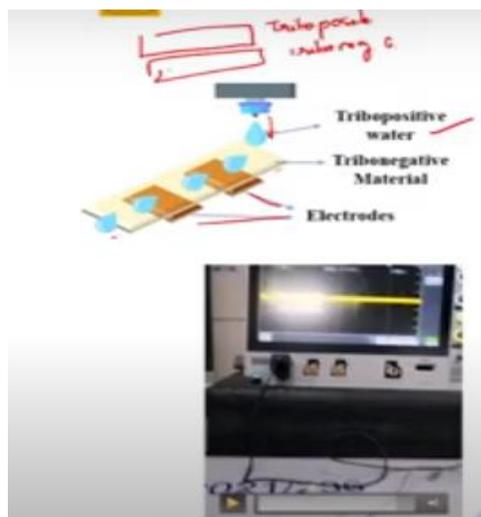


Now, the working principle of this Coriolis flow sensor is that the flow tubes are electromagnetically vibrated at their natural frequency. As the fluid flows through the vibrating tube, it experiences a Coriolis acceleration, causing the tubes to twist slightly. The twisting motion is proportional to the mass flow rate of the fluid. Sensors at the inlet and the outlet of the tubes detect this twisting as a phase shift between the vibrations at each end. The phase difference Δt between the inlet and the outlet vibration is directly proportional to the mass flow rate. The electronic unit processes this phase difference to calculate and output the mass flow rate. The vibration frequency of the tube is used to determine the fluid density. Temperature and sensors compensate for thermal effects and provide the process temperature data. So, these tube oscillations will also be helpful for the overall mechanism to maintain a kind of a uniform flow. The next important configuration is called a triboelectric nanogenerator-based flow sensor.

The principle behind the triboelectric nanogenerator is that it works on the principle of electrostatic charge. So we have a tribo-positive material and a tribo-negative material. So here, we directly induce a tribonegative material, and two electrodes are placed in it. We are trying to pour a water droplet into this particular system. So, these water droplets will flow in a particular direction, which will initiate a kind of charge.



This can be used to monitor the overall flow rate. If we have a kind of microrobotic system, the overall flow of the microrobotic system can be efficiently monitored using such a triboelectric nanogenerator. The interesting part of this triboelectric nanogenerator-based flow sensor is that this triboelectric nanogenerator-based integrated flow sensor can operate at a minimal level, so that when the water flows over it, the water becomes positively charged when it hits the triboelectric material. Hence, we can appropriately observe a change in its overall characteristics. Based on the change in characteristics, we can study the overall flow rate. So, in this particular video, we can observe that when the water flow hits the surface of a triboelectric negative material, the positive node of this particular water droplet allows us to continuously monitor the shift in the charge.



Now the triboelectric nanogenerators can be formed by combining two materials having a different electron affinity. When the fluid with tribo-negative and tribo-positive properties flows over the material with different electron affinities, electrical signals will be generated depending on the flow velocity, and the voltage signals will change. A higher velocity will generate a higher voltage. So this comes under the category of a self-generating system. This self-generating system has the capability to propel the micro-robotic systems appropriately.

So this is a kind of new technology that can be used for encapsulating these micro-robotic structures for self-powered systems. Now, let us discuss the haptic interface. The haptic interface is considered to be one of the key elements for a micro robotic system. So that we will discuss in detail in the next session.