Biomedical Ultrasound Fundamentals of Imaging and Micromachined Transducers

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Lecture – 56

Welcome to this lecture on ultrasonic sensors! Today, we'll explore what ultrasonic sensors are, how they work, their fabrication, and their applications.

To begin, ultrasonic sensors are electronic devices that use sound waves beyond the range of human hearing, typically between 20 kHz and 2 MHz, to measure distances or detect objects. One common example of a commercially available sensor is the HC-SR04. These sensors operate based on the principle of echolocation, much like how bats and whales navigate by emitting sound waves and interpreting the time it takes for those waves to bounce back after hitting an object.

One of the primary applications of ultrasonic sensors is in distance measurement. You've probably encountered them in modern cars when reversing, the sensor helps detect obstacles and warns the driver with sound alerts. Ultrasonic sensors are also widely used in industries for object detection and measurement purposes.

In terms of the electromagnetic spectrum, ultrasonic waves fall outside the range of visible light and operate at frequencies higher than what the human ear can detect. This slide also shows the wavelength spectrum from radio waves to gamma rays, and the frequency range from 10^4 Hz to 10^{20} Hz.

The history of ultrasonic sensors is fascinating. Their evolution began with the work of Swiss physicist Jean-Daniel Colladon and mathematician Charles-François Sturm, who used an underwater bell in Lake Geneva to calculate the speed of sound in water. The understanding of sound and ultrasound has developed over centuries, beginning with contributions from ancient figures like Pythagoras and Aristotle, who explored the relationship between pitch and frequency.

During World War I, high-frequency sound waves were first used for submarine detection by Paul Langevin. Later, in 1928, Sergei Sokolov proposed the concept of using ultrasound for flaw detection. In the 1940s and 1950s, inventors like Firestone, Sproule, and Trost made significant contributions to ultrasonic technology. By the 1950s, companies such as Krautkramer and Deutsch entered the market, sparking global competition.

The invention of piezoelectric materials, which generate an electric charge when mechanical stress is applied, played a crucial role in the development of ultrasonic sensors. Materials like quartz, aluminum nitride, zinc oxide, and PVDF (polyvinylidene fluoride) are key examples of piezoelectric substances.

The 1980s and 1990s saw significant advances in the miniaturization of ultrasonic sensors, which led to their widespread adoption in consumer electronics. These advancements have paved the way for ultrasonic sensors to become an integral part of modern technology, enabling accurate measurement and object detection across various industries.

In this particular experiment, a bell was used to measure how long it takes for its sound to travel and be heard, alongside firing a gun to determine the speed at which the gunshot sound could be heard. The experiment aimed to calculate distance based on the time taken for the sound to reach the listener, and remarkably, the calculated distance was very close to what we theoretically know today. This experiment lays the foundation for how ultrasonic sensors work.

Ultrasonic sensors, or transducers, consist of a transmitter and a receiver (which can also function as a transceiver). The transmitter emits sound waves, which bounce off an object and return to the sensor. The receiver then measures the time it takes for the sound to travel to the object and back. This process involves emitting sound waves (typically between 20 kHz and 65 kHz), bouncing off objects, measuring the return time, and calculating the distance. The time interval between sending and receiving the sound is very short, often measured in microseconds.

To calculate the distance, the sensor multiplies the time it takes for the sound to travel to and from the object by the speed of sound. The resulting data is output as distance information, which can be used in various applications such as obstacle detection, object positioning, and navigation.

There are several types of ultrasonic sensors:

Analog Sensors: These sensors provide a continuous voltage output proportional to the distance of the object, enabling precise control and easier integration with other systems.

Diffuse Sensors: These sensors combine the transmitter and receiver into a single housing. They detect objects by measuring the reflected sound wave and are suitable for short-range applications, being less sensitive to object orientation.

Through-Beam Sensors: These sensors use separate transmitters and receivers. Object detection occurs when the sound wave between the transmitter and receiver is interrupted, making them ideal for long-range applications and precise object detection.

Retro-Reflective Sensors: Similar to diffuse sensors, these combine the transmitter and receiver in a single unit but use a reflector behind the object to improve the strength of the reflected sound waves. This allows for longer-range detection and better performance in environments with dust or noise.

The heart of an ultrasonic sensor is the piezoelectric transducer, which converts electrical signals into sound waves and vice versa. The material commonly used for this purpose is lead zirconate titanate (PZT), a highly effective piezoelectric material. However, various other materials are also used depending on the desired properties of the transducer. The piezoelectric transducer plays a critical role in the functioning of the sensor, making it the core component that enables the sensor's operation.

The control unit, often referred to as the "brain" of the ultrasonic sensor, manages essential tasks such as generating signals for sound wave emission, amplifying received echo signals, and processing data from object detection or distance measurement. The housing of the sensor serves to protect internal components from environmental factors, and its material—whether plastic, metal, or a combination depends on the application and operating conditions.

Additional components of the sensor can vary based on the specific type. For instance, in retroreflective sensors, reflectors are used to enhance the reflected sound waves, improving range and performance. An Analog-to-Digital Converter (ADC) is typically present to convert the sensor's analog signals into a digital format for easier processing.

Several important parameters influence ultrasonic sensor performance:

Operating Range: The distance over which the sensor can detect objects.

Beam Angle: Usually around 15 degrees, this determines the spread of the emitted sound wave.

Operating Frequency: Typically between 20 kHz and 200 kHz.

Blind Zone: The minimum distance within which the sensor is unable to detect objects.

Power Consumption: The amount of energy required for the sensor to operate.

Environmental Factors: Conditions like temperature, humidity, and dust can affect the sensor’s performance.

The sensor's output can be either digital or analog, depending on the type and functionality. The key performance indicators include:

Accuracy: The ability to measure the actual distance to an object.

Resolution: The smallest change in distance that the sensor can detect.

Response Time: The time it takes for the sensor to detect an object and provide an output signal.

When selecting an ultrasonic sensor, several criteria should be considered:

Sensing Properties: This includes rated operating distance (how far the sensor can detect objects) and repeatability (the sensor’s ability to consistently provide the same measurement results for a given distance).

Carrier Signal: The blind zone, or the area from the sensor face where no objects can be detected, and the transmitter frequency, which defines the range of broadcast and received signals.

Electrical Power Options: Ultrasonic sensors can operate on AC or DC, with load configurations for both types (AC/DC with NPN or PNP DC load options).

Wire Configurations: Different configurations include 2-wire, 3-wire, 4-wire, with NPN or PNP options.

Body Material: The sensor body can be cylindrical with a threaded barrel, or rectangular/block-shaped depending on the application.

Piezoelectric micromachined ultrasonic transducers (PMUTs), which are fabricated using advanced microengineering technologies, also play a vital role in ultrasonic sensing. Electrical connections like flexible cables, connectors, and terminals are crucial for transmitting signals from the sensor to external systems or electronics.

The working principle involves signal generation, where the sensor receives a trigger pulse, causing it to generate a burst of acoustic signals. These signals travel toward the target, reflect back, and are received as an echo. A piezoelectric crystal within the sensor is responsible for this action, vibrating at a specific frequency when triggered and converting the electrical signal into ultrasound waves, which are then used for detection or measurement.

This process illustrates how the piezoelectric effect is harnessed in ultrasonic sensors to convert electrical energy into mechanical vibrations and vice versa, forming the core functionality of these sensors.

The transducer in an ultrasonic sensor works by using vibrating piezoelectric crystals to emit and receive ultrasound waves. When these ultrasound waves are emitted from the sensor housing into the environment, they interact with objects, and some of the waves are reflected back toward the sensor. This process is known as **echo reception**.

The returning sound waves are received by the same piezoelectric crystal. Due to the energy loss during travel and reflection, the vibrations caused by the reflected waves are at a lower amplitude. This vibration converts the reflected sound energy back into electrical energy, completing the transduction process. In essence, the sensor starts with electrical energy, converts it to acoustic energy, and after interacting with an object, the reflected waves are converted back into electrical signals.

As the sound waves reflect back, the varying pressure of the received sound waves is translated into voltage fluctuations across the piezoelectric material. To ensure the sensor provides accurate and useful data, it must undergo calibration.

Calibration Types:

1. **Zero-point calibration**: This ensures accurate measurement by correcting any initial offsets or errors in the system.
2. **Sensitivity adjustment**: Fine-tuning the sensor's response to adapt to various environmental conditions.
3. **Temperature compensation**: Ultrasonic sensors can be affected by temperature changes. Calibration factors are applied to account for these variations and maintain accuracy.

Calibration can be done in several ways depending on the sensor type and manufacturer. For instance, a **potentiometer** allows for manual adjustment using a physical knob to fine-tune the sensor's output. There's also **software calibration**, where internal parameters are adjusted using manufacturer-provided tools through a communication interface.

In practical applications, when you purchase an ultrasonic transducer, the output is often displayed directly as a distance or measurement data. However, the sensor's raw output is in the form of changes in resistance, voltage, or current, which needs to be converted from analog to digital format before you can read it as a distance measurement.

Example of Calibration Methods:

- **Potentiometer adjustment**: A manual process where a physical knob is used to adjust sensor output.
- **Software configuration**: Allows for fine-tuning internal parameters via software tools, which provide more precise calibration through a digital interface.

On platforms like Arduino IDE, sensors like the HC-SR04 are simple to use and display real-time distance measurements. This demonstrates how the ultrasonic sensor data can be visualized after calibration.

Fabrication of Ultrasonic Transducers: An example of fabricating an ultrasonic transducer is using thin-film deposition techniques. Here's a typical process:

1. Start with a **substrate**.
2. Deposit a layer of **platinum** on the substrate, which acts as the bottom electrode, and pattern the platinum layer.
3. Deposit **PZT** (lead zirconate titanate), a piezoelectric material, on top of the platinum layer.
4. Pattern the PZT layer.
5. Deposit another platinum layer on top of the PZT, creating a sandwich structure where the PZT material is sandwiched between two platinum electrodes—one at the bottom and one at the top.

This layered structure forms the core of the piezoelectric transducer, enabling it to convert electrical signals into acoustic waves and vice versa.

In summary, ultrasonic sensors, through their piezoelectric transducers, use precise calibration and tuning techniques to ensure accurate object detection and distance measurement, while advancements in fabrication methods, such as thin-film deposition, enable the creation of high-performance sensors.

Let’s now look at how a piezoelectric micromachined ultrasound transducer (PMUT) or a general piezoelectric ultrasound transducer can be fabricated.

Fabrication Process:

Start with a PZT Layer: After creating your piezoelectric layer using PZT (lead zirconate titanate), you can then apply a thin layer of gold on top. Over this gold layer, you can add a polyimide layer for added flexibility. At this point, you can release the entire structure from the substrate, resulting in a flexible piezoelectric ultrasound transducer. This type of transducer can be very useful for flexible electronic applications.

Micromachining Technique: Another approach to creating a piezoelectric ultrasound transducer involves micromachining techniques, typically starting with an SOI (Silicon on Insulator) wafer. Here's an outline of the key steps:

Begin with an SOI wafer and grow a silicon oxide layer using thermal oxidation.

Deposit titanium and platinum layers. The titanium serves as an adhesion layer, improving the bond between the platinum and the substrate.

Use a lift-off technique to remove excess material and pattern the platinum.

Deposit the PZT layer and pattern it.

Complete the fabrication by performing deep reactive ion etching (DRIE) on the silicon to form the final structure of the transducer.

In general, to fabricate an ultrasonic transducer, we typically start with a silicon wafer.

Step-by-Step Process:

Oxide Layer Formation: Begin with a silicon wafer and grow a thin layer of oxide on it, resulting in an oxidized silicon wafer.

Bottom Electrode Deposition: Deposit a thin metal layer (platinum or a similar material) on the oxidized wafer, which will serve as the bottom electrode.

Patterning of Bottom Electrode: Use lithography techniques to pattern the metal, defining the shape of the bottom electrode. At this point, you have a metal layer patterned onto the oxidized wafer, forming the foundation for the transducer.

PZT Deposition: Next, deposit a piezoelectric material, such as PZT, over the bottom electrode. Pattern the PZT layer to ensure it makes electrical contact with the bottom electrode, forming the core piezoelectric element.

Top Electrode Deposition: Deposit a second metal layer (platinum, for example), which will serve as the top electrode. This layer will be patterned to create electrical contact points with the PZT layer.

At this stage, you have a sandwich structure: a piezoelectric material (PZT) between two electrodes (top and bottom). The bottom electrode extends laterally, making electrical contact with the PZT layer.

Micromachining (DRIE): Perform micromachining using deep reactive ion etching (DRIE). This technique allows precise etching of the silicon to create the required structures, such as diaphragms, which enable the transducer to detect and convert mechanical pressure into electrical signals.

Working Principle: When pressure is applied to the transducer’s diaphragm (which consists of the PZT material sandwiched between the electrodes), the diaphragm bends. This bending action induces a voltage change across the top and bottom electrodes due to the piezoelectric effect. The voltage change is then interpreted as a signal, corresponding to the pressure or distance measurement.

Emerging Fabrication Techniques:

Stereolithography (3D Printing): 3D printing techniques are emerging as a powerful tool in fabricating customized sensors. Layers of material are fused together to form the structure of the sensor, allowing for flexibility in design.

Hybrid Techniques: One popular approach is to deposit PZT film on micromachined silicon substrates, which allows for high-performance miniaturized devices. In such designs, you can incorporate multiple diaphragms on a single silicon substrate, creating an array of sensors for enhanced performance.

By using these fabrication methods, advanced piezoelectric ultrasound transducers can be produced, which have applications ranging from medical imaging to industrial sensors.

Let’s now wrap up the discussion on ultrasonic sensors and their wide-ranging applications.

Each diaphragm of a piezoelectric micromachined ultrasonic transducer (PMUT) can have its own piezoelectric material. Integrating electronic components with sensor structures through techniques like 3D printing enhances the sensor's functionality, making it more versatile and efficient.

Applications of Ultrasonic Imaging: One of the most well-known uses of ultrasonic sensors is medical imaging, where ultrasound is extensively used for non-invasive visualization of internal body structures. It is commonly employed for diagnostic imaging, such as monitoring pregnancies or assessing organ conditions. Additionally, ultrasound has therapeutic applications. For instance, high-intensity focused ultrasound (HIFU) is used for tumor ablation, a technique that can destroy tumors without invasive surgery. Recent advancements even allow for the non-invasive destruction of tumors within the skull, a breakthrough in cancer therapy.

In blood flow monitoring, Doppler ultrasound is widely used. Doppler sensors measure the blood flow by detecting the frequency shift in the reflected sound waves as they bounce off moving blood cells. This technique is vital for assessing vascular conditions and identifying circulatory abnormalities, providing essential data for medical diagnosis.

Beyond medical uses, ultrasonic sensors are also utilized in various industrial and everyday applications:

Liquid level measurement in tanks and reservoirs.

Leak detection in pipelines, whether for oil, water, or other fluids.

Automotive applications, such as parking assistance, airbag deployment, and adaptive cruise control systems, which rely on ultrasonic sensors to ensure driver safety and enhance vehicle functionality.

Practical Example: If you want a hands-on experience with ultrasonic sensors, an excellent option is to experiment with the popular HC-SR04 sensor. I always encourage students to pair theoretical learning with practical experiments to fully grasp the functionality of a sensor. The HC-SR04 operates at a working voltage of 5V with a current draw of around 15mA. Its operating frequency is 40 kHz, with a range between 2 cm and 4 meters. A trigger input signal of a 10-microsecond TTL pulse is required for operation, and its dimensions are 45 mm x 20 mm x 15 mm. You can connect this sensor to an Arduino board and run a simple program to measure distance and observe the sensor in action.

This type of hands-on experimentation not only reinforces your understanding of how the sensor works but also prepares you for real-world applications. I'll be happy to provide the necessary program code and guide you through the setup. By trying it out, you'll gain valuable insights into how to implement and test ultrasonic transducers in various projects.

Conclusion: In this lecture, we’ve explored the fabrication techniques of ultrasonic transducers, including micromachining and deep reactive ion etching (DRIE) to create diaphragms for miniaturized sensors. We’ve also covered how ultrasonic sensors are used in a variety of fields, from medical imaging and therapy to industrial applications such as oil leak detection and automotive safety. Practical examples like the HC-SR04 help bridge the gap between theory and application, allowing you to experiment with and understand these sensors on a deeper level.