



Advancements and Applications of Pressure Sensors in Automotive Engineering

Vinay Nagarad Dasavandi Krishnamurthy

Software Engineer Bosch USA Michigan- USA
vinayndk9@gmail.com

ABSTRACT

Pressure sensors play a pivotal role in various automotive applications, spanning from engine performance optimization to safety enhancements. This paper provides an overview of pressure sensors used in automobiles, highlighting their diverse range and applications. It explores the wide-ranging capacity of pressure sensors, which can measure pressures from as low as 10 kPa in vacuum systems for evaporative fuel leak detection to as high as 180 MPa in diesel common-rail fuel pressure systems, representing an 18,000:1 variation in fullscale pressure range measurement requirements [1][2]. Different types of pressure sensors, including manifold absolute pressure (MAP) sensors, barometric pressure sensors, fuel rail pressure sensors, and tire pressure monitoring system (TPMS) sensors, are discussed, along with their operating principles, technologies, and applications in automotive systems. Special attention is given to piezoresistive and capacitive pressure sensors, examining their construction, advantages, and applications in automotive environments. The abstract concludes with insights into the importance and prevalence of pressure sensors in automotive engineering.

Keywords: Pressure sensors, Automotive applications, Manifold absolute pressure sensor, Piezoresistive sensors, Capacitive sensors, Operating principles, Applications, Tire pressure monitoring system (TPMS), Fuel rail pressure sensor, Barometric pressure sensor, Transmission fluid pressure sensor.

INTRODUCTION

Pressure sensors find a multitude of applications in the automotive industry, exhibiting a wide-ranging capacity to measure pressures from as low as 10 kPa in vacuum systems for evaporative fuel leak detection to as high as 180 MPa in diesel common-rail fuel pressure systems. This represents a staggering 18,000:1 variation in the full-scale pressure range measurement requirements. It's evident that a sensor designed for the lower range of 10 kPa won't possess the robustness necessary for the demanding environment of a 180-MPa fuel pressure application. Consequently, various pressure sensor technologies have been developed to address these diverse needs [1][2]. Pressure sensors rank second in terms of unit sales and sixth in gross sales revenue, positioning them prominently in the automotive sensor market. In 1999, pressure sensors constituted 9% of all automotive sensor sales revenue in North America, with unit sales reaching 78 million sensors [7].

LITERATURE REVIEW

Pressure sensors are vital components in automotive systems, facilitating various functions ranging from engine performance optimization to safety features. Here's an overview of pressure sensors used in automobiles

A. Pressure Sensors used in Automotive

- 1) Manifold Absolute Pressure (MAP) Sensor: The MAP sensor measures the absolute pressure within the intake manifold. This information helps the engine control unit (ECU) calculate engine load and adjust fuel injection timing and ignition advance accordingly. MAP sensors are critical for optimizing engine performance and fuel efficiency.

- 2) Barometric Pressure Sensor: Barometric pressure sensors measure the ambient air pressure outside the vehicle. They assist the ECU in compensating for changes in altitude, ensuring accurate air-fuel ratio and engine performance under varying environmental conditions.
- 3) Fuel Rail Pressure Sensor: Fuel rail pressure sensors monitor the pressure of fuel in the fuel rail. They provide feedback to the ECU for precise fuel delivery, optimizing engine performance, and emissions control.
- 4) Transmission Fluid Pressure Sensor: Transmission fluid pressure sensors monitor the hydraulic pressure within the transmission system. They help ensure smooth gear shifts and prevent damage to the transmission components.
- 5) Tire Pressure Monitoring System (TPMS) Sensor: TPMS sensors measure the air pressure in each tire and alert the driver to underinflated tires. TPMS sensors enhance vehicle safety, improve tire longevity, and optimize fuel efficiency by maintaining proper tire pressure.
- 6) Oil Pressure Sensor: Oil pressure sensors monitor the oil pressure within the engine lubrication system. They help detect oil pump failures, low oil levels, or oil leaks, preventing engine damage due to inadequate lubrication.

OPERATING PRINCIPLES AND TECHNOLOGIES

- 1) Piezoresistive Sensors: These sensors utilize the piezoresistive effect, where the resistance of a material changes in response to applied pressure. Piezoresistive pressure sensors offer high sensitivity, accuracy, and reliability, making them suitable for automotive applications.
- 2) Capacitive Sensors: Capacitive pressure sensors measure pressure by detecting changes in capacitance between two conductive plates. They are known for their high precision and stability, particularly in low-pressure applications.
- 3) Strain Gauge Sensors: Strain gauge pressure sensors measure pressure by detecting the strain or deformation of a thin metal diaphragm. They offer good accuracy and are commonly used in automotive fuel systems and exhaust gas recirculation (EGR) systems.

A. Piezoresistive sensors

Piezoresistive pressure sensors are a type of pressure sensor that operates based on the piezoresistive effect, which refers to the change in electrical resistance of a material when subjected to mechanical stress or strain. These sensors are widely used for measuring pressure in various applications due to their high sensitivity, accuracy, and reliability. Here are some key points about piezoresistive pressure sensors:

- 1) Operating Principle: Piezoresistive pressure sensors consist of a diaphragm or membrane that flexes in response to applied pressure. The diaphragm is typically made of a semiconductor material such as silicon, which exhibits piezoresistive properties. As pressure is applied to the diaphragm, it deforms, causing changes in the resistance of the piezoresistive elements embedded within the diaphragm. These changes in resistance are directly proportional to the applied pressure and can be measured using appropriate electronic circuitry. The strain-sense elements are electrically connected into a Wheatstone bridge circuit, thereby providing a means of detecting pressure acting on the diaphragm. Modern sensors feature on-chip digital electronics which provide signal conditioning, programmable calibration of span and offset, built-in compensation for nonlinearity and temperature effects, ratiometric output signal, high accuracy over a wide temperature range and nearly identical part-to-part interchangeability.
Construction: Piezoresistive pressure sensors are constructed using microfabrication techniques, which allow for precise control over the dimensions and properties of the sensor elements. The diaphragm is often etched or machined from a silicon wafer, and piezoresistive elements, typically made of doped silicon, are diffused or deposited onto the surface of the diaphragm. Electrical connections are then made to the piezoresistive elements to measure changes in resistance.
- 2) Advantages: Piezoresistive pressure sensors offer several advantages, including high sensitivity, fast response times, and wide pressure measurement ranges. They are also relatively compact, lightweight, and cost-effective compared to other types of pressure sensors. Additionally, piezoresistive sensors can operate over a wide temperature range and exhibit minimal hysteresis and drift, making them suitable for demanding industrial and automotive applications.

- 3) **Applications and range:** Piezoresistive pressure sensors are used in a wide range of applications across industries such as automotive, aerospace, medical, and industrial automation. In automotive applications, they are employed for measuring engine manifold pressure, tire pressure, fuel rail pressure, and hydraulic system pressure. For example, they may be employed in tire pressure monitoring systems (TPMS) to measure the air pressure inside tires, typically ranging from around 100 kPa to 400 kPa (15 to 60 psi). Piezoresistive pressure sensors are also utilized in various medium-pressure automotive systems, such as engine intake manifold pressure measurement, fuel rail pressure sensing, and exhaust gas pressure monitoring. In these applications, the pressure range typically extends from a few hundred kPa to several thousand kPa. For example, in engine management systems, piezoresistive pressure sensors may measure intake manifold pressure. Some automotive systems require piezoresistive pressure sensors capable of measuring high-pressure conditions. For instance, in diesel common-rail fuel injection systems, the pressure inside the fuel rail can reach several tens of thousands of kilopascals (kPa) or even over 100 MPa. In aerospace, they are used for aircraft altitude and airspeed measurement, as well as in cabin pressure monitoring systems. In medical devices, piezoresistive pressure sensors are utilized for blood pressure monitoring, respiratory therapy, and infusion pumps, among other applications. In automotive systems, piezoresistive pressure sensors are commonly used to measure low to moderate pressures.
- 4) **Calibration and Compensation:** To ensure accurate pressure measurement, piezoresistive pressure sensors may require calibration to account for variations in temperature, humidity, and other environmental factors. Additionally, temperature compensation techniques may be employed to minimize the effects of temperature variations on sensor performance.

B. Capacitive pressure sensors

Capacitive pressure sensors are becoming increasingly prevalent in automotive applications due to their high accuracy, reliability, and compatibility with harsh operating conditions. These sensors utilize the principle of capacitance change in response to variations in pressure, providing precise measurements across a wide range of pressures. Here's an overview of capacitive pressure sensors in automotive use:

- 1) **Operating Principle:** Capacitive pressure sensors measure pressure by detecting changes in capacitance between two conductive plates or electrodes. When pressure is applied, the distance between the plates changes, altering the capacitance. This change in capacitance is then converted into an electrical signal proportional to the applied pressure.
- 2) **High Accuracy:** Capacitive pressure sensors offer excellent accuracy and repeatability, making them ideal for demanding automotive applications where precise pressure measurements are required. Their ability to provide consistent and reliable readings contributes to improved vehicle performance, efficiency, and safety.
- 3) **Wide Pressure Range:** Capacitive pressure sensors can be designed to measure a broad range of pressures encountered in automotive systems. They are suitable for low-pressure applications, such as tire pressure monitoring, as well as high-pressure applications, such as engine intake manifold pressure sensing and fuel system pressure monitoring.
- 4) **Temperature Stability:** Capacitive pressure sensors often feature temperature compensation mechanisms to ensure stable performance over a wide temperature range. This temperature stability is critical for maintaining sensor accuracy and reliability in the varying thermal conditions experienced in automotive environments.
- 5) **Compact and Lightweight:** Capacitive pressure sensors are typically compact and lightweight, making them well-suited for integration into modern vehicle designs. Their small form factor allows for flexible installation options while minimizing space and weight constraints.
- 6) **Robustness and Durability:** Capacitive pressure sensors are designed to withstand the harsh operating conditions encountered in automotive applications, including temperature extremes, vibration, and exposure to moisture, dust, and contaminants. Their robustness and durability make them a reliable choice for various automotive systems and components. They are commonly used for tire pressure monitoring, engine intake manifold pressure sensing, exhaust gas recirculation (EGR) system monitoring, brake system pressure sensing, and more.

OVERVIEW OF SENSORS AND APPLICATIONS

Piezoresistive micromachined sensors are extensively used to measure engine manifold pressure (absolute and barometric), turbo-boost pressure, and evaporative fuel leak pressure. Capacitive touch-mode micromachined sensors are used to measure tire pressure inside the rotating wheel and engine oil pressure (two applications where accurate indication of the zero point isn't required). Capacitive ceramic-module sensors, are used to measure brake fluid pressure (for cruise control disengagement and ABS braking regulation), suspension hydraulic pressure, and A/C compressor pressure. Piezoresistive polysilicon-on-steel sensors are used to measure common-rail FI (fuel injection) pressure, and vehicle suspension dynamic control hydraulic pressure [1].

CONCLUSION

In conclusion, the extensive utility of pressure sensors in automotive applications underscores their indispensable role in modern vehicle technology. From optimizing engine performance to ensuring safety and reliability, pressure sensors contribute significantly to the functionality and efficiency of automotive systems. The wide-ranging capacity of pressure sensors to measure pressures spanning from vacuum systems to high-pressure fuel systems reflects their adaptability and versatility in addressing diverse engineering challenges. Moreover, the evolution of various pressure sensor technologies, including piezoresistive and capacitive sensors, underscores ongoing efforts to enhance sensor performance, accuracy, and reliability. As automotive engineering continues to evolve, pressure sensors will remain integral components, driving innovation and advancements in vehicle design, performance, and safety standards. This paper emphasizes the importance of pressure sensors in automotive engineering and highlights their critical role in shaping the future of automotive technology.

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