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Aging Mechanisms and Protective Measures of Typical Mechanical Sensors

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Abstract: This paper provides a systematic review of the aging mechanisms and protective strategies for mechanical sensors, which are widely used in industrial production and various application scenarios. It focuses on major types of sensors—namely piezoresistive, piezoelectric, capacitive, optical, electromagnetic, and triboelectric sensors. The study conducts an in-depth analysis of how key environmental factors such as temperature, humidity, mechanical stress, and electromagnetic interference induce performance degradation in core materials and structural failures. These aging processes commonly lead to issues such as zero-point drift, sensitivity variation, signal attenuation, and even complete sensor failure, all of which significantly undermine measurement accuracy and device longevity. The paper further summarizes a range of countermeasures, including thermal shielding and heat dissipation optimization, hermetic packaging, electromagnetic shielding, structural buffering design, material modification, compensation algorithms, and periodic calibration or replacement. The study highlights the critical importance of understanding the specific aging mechanisms of each sensor type and implementing effective protection strategies to ensure the reliable operation of automated systems.

Keywords: Mechanical Sensors, Aging, Piezoresistive, Piezoelectric, Triboelectric

1. Introduction

With the continuous advancement of industrial automation, leading enterprises across various industrial sectors are increasingly investing in automated production facilities, such as unmanned workshops and “dark factories,” to enhance productivity and reduce operational costs. In the construction of such automated production lines, a large number of sensors are employed to collect data and support the operation of the system. Among them, mechanical sensors are extensively applied in key stages such as material handling, component assembly, and product inspection [1-3], accounting for a significant proportion of all sensors used. Moreover, mechanical sensors are widely utilized in a variety of other industries as well. Currently, the mechanical sensors in use across production and daily life mainly include piezoresistive sensors (typically made of P-type silicon [4], carbon nanotubes [5], graphene [6], among others [7]), piezoelectric sensors [8], capacitive sensors [9,10], triboelectric sensors [11,12], optical mechanical sensors [13-15], and electromagnetic induction sensors [10,16-18], as illustrated in Figure 1.

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Given the vast scale of the current sensor market, sensor aging has become an issue that can no longer be overlooked. Mechanical sensors play a critical role across a wide range of fields, but the complex and often harsh operating environments pose significant challenges to their reliability, particularly in terms of accuracy and response speed. As a result, the aging mechanisms, impacts, and preventive measures associated with mechanical sensors have attracted increasing attention from researchers [19]. Building upon previous studies, this paper provides a concise summary and analysis of the potential causes and effects of sensor aging in both industrial and everyday settings, and proposes several potential protective strategies.

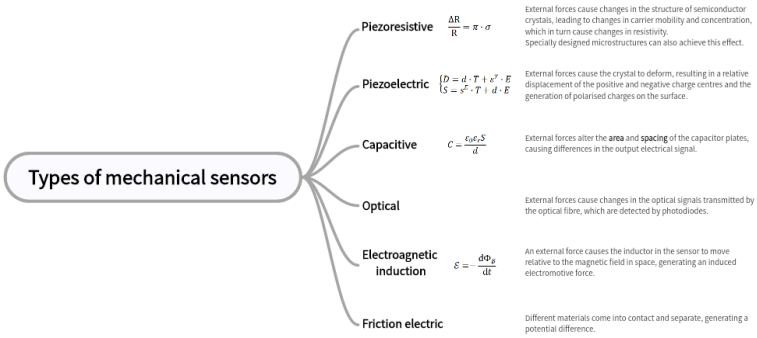


Figure 1. Types and working principles of mechanical sensors

2. Aging mechanisms of various types of sensors

2.1. Piezoresistive sensors

Piezoresistive sensors operate primarily based on the piezoresistive effect of silicon; however, materials with specialized microstructures can also exhibit similar piezoresistive behavior. The aging of piezoresistive sensors is mainly influenced by factors such as high temperature, intrinsic material properties, sensor structure, and external mechanical forces [20].

2.1.1. PN junction leakage current

Due to manufacturing defects or ion implantation processes, PN junction leakage current may occur, resulting in zero-point temperature drift and nonlinear errors. Rising temperatures significantly exacerbate this leakage current [21]. According to the study by Balavalad et al.[22], when the operating temperature exceeds 100 °C, the PN junction leakage current in piezoresistive pressure sensors increases sharply. This ultimately leads to output instability, reduced service life, and even sensor failure.

2.1.2. Assembly stress and thermal stress

Piezoresistive pressure sensors typically connect four p-type piezoresistors in a Wheatstone bridge configuration, which are embedded or diffused into a single-crystal silicon substrate. This process inevitably generates stress between various components. During natural aging, the initial assembly stress at the junctions of the composite structure gradually changes—often involving stress relaxation. This leads to output signal offset in sensors that were previously calibrated, even when the applied pressure is zero. Moreover, the magnitude of this offset error increases with rising temperature. As a result, the sensor may require recalibration or even replacement [21].

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During the manufacturing process, mismatches in the coefficients of thermal expansion among different materials can lead to deformation and internal stress under high-temperature operating conditions—an effect known as thermal expansion mismatch. This not only causes zero-point drift and measurement deviation but may also result in the formation of microcracks within the structure, potentially leading to permanent damage.

Based on this principle, newly manufactured sensors can undergo controlled aging treatments—such as thermal cycling and periodic vibration—to help the piezoresistive sensor reach a more stable performance phase [23]. In addition, differential measurement configurations can effectively mitigate the temperature sensitivity caused by thermal expansion within the sensor structure [24].

2.1.3. Thermal drift

At the hardware level, compensation resistors can be incorporated into the bridge circuit to mitigate thermal drift. At the software level, higher-precision temperature drift correction can be implemented through programming [25].

2.2. Piezoelectric sensors

2.2.1. Curie temperature

For piezoelectric sensors, when the temperature rises above the Curie temperature, the microcrystalline structure of piezoelectric materials—including piezoelectric ceramics—undergoes a phase transition from the ferroelectric phase (characterized by spontaneous polarization) to the paraelectric phase (where polarization disappears), a process known as depolarization. This transition is generally irreversible, and the piezoelectric coefficients of the material may decline significantly [26]. Even if the temperature does not exceed the Curie point, piezoelectric materials can still experience varying degrees of performance degradation under relatively high-temperature operating conditions [27]. Under such circumstances, the sensor may exhibit attenuated response signals or even complete failure.

However, doping with impurity elements, heat treatment, and defect engineering can increase the Curie temperature of the material and improve its durability and mechanical properties [28].

2.2.2. Humidity level

For piezoelectric mechanical sensors, in humid environments, water molecules may react with the surface of the piezoelectric material, causing oxygen atoms to detach from the lattice and enter the solution or gas phase, thereby forming oxygen vacancies. These oxygen vacancies interfere with domain wall motion through pinning effects, adversely affecting the performance of the piezoelectric material [29,30].

2.2.3. External electromagnetic field

For ferroelectric piezoelectric materials, applying a strong electric field opposite to the polarization direction can cause domain disordering and loss of piezoelectric properties. When the amplitude of an alternating electric field exceeds the depolarization threshold, the piezoelectric constant of the material continuously degrades [31].

Additionally, external electric fields may generate atomic hydrogen through the electrolysis of surface water films on the device, leading to reduced resistivity, increased dielectric loss, and

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deterioration of electrical performance [8].

2.2.4. Stress cycle

Frequent impacts and vibrations can cause poor adhesion between the electrodes and the piezoelectric material, resulting in inaccurate measurements. Excessive impacts may induce microcracks inside the piezoelectric material, causing failure. Even under normal use, repeated mechanical stress after a certain number of cycles can cause microcracks that degrade material performance.

For this aging mechanism of piezoelectric sensors, regular inspection and timely replacement of damaged sensors are highly effective preventive measures during production processes.

2.3. Capacitive sensors

2.3.1. Temperature

Similar to piezoresistive sensors, capacitive mechanical sensors face a series of challenges caused by high temperatures. In many capacitive sensors, the dielectric layer between the capacitor plates is sealed [9]. When the ambient temperature undergoes significant changes, the dielectric layer—especially in sensors where the layer is filled with air—is prone to thermal expansion, resulting in capacitance drift that adversely affects measurement accuracy.

2.3.2. External electromagnetic field

The working principle of capacitive sensors, which relies on electric fields, leads to two major vulnerabilities: first, sensitivity to nearby objects—regardless of whether they are conductive or not—as these objects can alter the electric field distribution or introduce stray capacitance in parallel with the measurement capacitance, thereby interfering with the measurement results; second, susceptibility to low-intensity electromagnetic interference, since the sensor's high impedance and the "antenna effect" of its wiring can couple external electromagnetic fields, causing noise or signal drift.

To address these issues, common approaches include the use of shielding structures (such as conductive encapsulation layers), differential electrode designs (to cancel common-mode interference), filtering algorithms (e.g., band-pass filtering and digital demodulation), and novel materials (such as flexible shielding dielectrics or high-permittivity dielectrics) to suppress interference. These strategies help improve environmental adaptability while maintaining high sensitivity. The Faraday cage shielding effect employed during shielding requires the installation of conductive components outside the sensor, which may introduce parasitic capacitance with the capacitor plates. To mitigate this, Bekir et al. proposed a method that separates the shielding layer from the sensing electrodes using a relatively rigid passive region (e.g., a silicone layer), thereby reducing variations in parasitic capacitance caused by deformation and thus diminishing the impact of parasitic capacitance noise [32].

2.3.3. Stress cycle

Gu et al. studied capacitive mechanical sensors that use PDMS as the supporting dielectric layer [10]. Under prolonged cyclic mechanical stress, the supporting material undergoes irreversible plastic deformation, causing zero-point drift in the capacitive sensor. In such cases, the sensor

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requires comprehensive recalibration or partial component replacement to ensure that the correspondence between the electrical signal and the mechanical input remains intact.

2.4. Triboelectric mechanical sensors

2.4.1. Temperature (thermal) and structural design

The core working principle of triboelectric mechanical sensors is contact electrification (CE), where two different materials become electrically charged on their surfaces due to charge transfer when they come into contact and then separate.

At elevated operating temperatures, both the short-circuit current and output power of triboelectric components decrease [33]. Lu et al. experimentally observed that when the temperature exceeds a certain threshold (>100 °C), the electrical output signal of the triboelectric sensor they studied rapidly diminishes. This performance degradation is attributed to a reduction in the relative permittivity of the triboelectric materials and to temperature-induced changes in material defects that enhance their antistatic behavior. These factors collectively impair the performance of triboelectric mechanical sensors. Therefore, temperature is a critical factor contributing to the aging of triboelectric sensor performance.

In addition, the sensor's structural design may inherently affect its performance. Wang et al. [34] demonstrated that, compared to sensors utilizing the contact-separation mode, those operating in sliding mode exhibit a larger contact area during relative motion of the friction materials. This increased contact area reduces the loss of effective surface charge caused by thermionic emission, thereby improving sensor performance.

Therefore, for triboelectric mechanical sensors, in addition to reducing excessive heat in the operating environment through thermal shielding measures, rational structural design is also crucial.

2.4.2. Humidity and temperature

Water can infiltrate the gaps between the positive and negative triboelectric layers, where water vapor condenses on the contact surfaces of the triboelectric layers to form a thin conductive film. This thin water layer increases the conductivity between the triboelectric layers, facilitating faster transfer and neutralization of triboelectric charges, which in turn weakens the sensor's output signal intensity. Additionally, water vapor in the air accelerates the charge dissipation on the triboelectric layers. In experiments conducted by Wang et al., when the relative humidity (RH) increased from 15% to 95%, the output voltage of the triboelectric element sharply decreased by 90% [35].

To address the above issues, performance of triboelectric mechanical sensors under high-humidity conditions can be improved through sensor encapsulation, surface modification of the triboelectric layers to enhance hydrophobicity, the use of moisture-conductive materials, or by leveraging interactions between water and polymer triboelectric materials to increase surface charge density [36].

In the study by Zhang et al., the charge transfer amount and charge retention capability of PDMS naturally aged for 17 months in an unsealed container at room temperature significantly decreased, accompanied by a reduction in dielectric constant and storage modulus. The fundamental cause of these property changes is chain scission of the Si–O bonds on the PDMS surface, with environmental temperature variations being the primary inducing factor [37].

To mitigate the aging of PDMS, conductive fillers such as graphene, carbon nanotubes, or metal nanoparticles can be incorporated to improve electrical conductivity, while the addition of silica can

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enhance mechanical properties. Furthermore, for such sensors, the use of dielectric materials with superior performance can also be explored to reduce the impact of material aging on sensor functionality.

2.5. Other

Using more hermetic packaging methods and controlling the thickness of surface layers during manufacturing can effectively suppress temperature- and humidity-induced aging mechanisms in optical mechanical sensors [38].

For magnetic mechanical sensors based on Faraday's electromagnetic induction law or the Hall effect, external electric field variations affect carrier movement and cause measurement errors. Similar to capacitive sensors, shielding techniques can be employed to protect the sensor as a whole [39].

Chen et al. coupled a pressure-sensitive capacitor with a resonant circuit [40]. Changes in capacitance caused by applied pressure induce shifts in the circuit's resonant frequency, allowing wireless detection of frequency shifts to infer the pressure value. This sensor can be applied for physiological monitoring of clinical patients. During cyclic testing, the sensor exhibited capacitance drift attributed to aging, likely caused by liquid infiltration and repeated mechanical stress. Replacing the substrate material and implementing enhanced packaging may help mitigate these aging issues. Additionally, real-time compensation can be achieved by characterizing the signal drift as a function of time.

3. Conclusion

Through the preceding discussion of the working principles and aging causes of various types of mechanical sensors, certain commonalities in their aging mechanisms and manifestations can be identified. In this section, we summarize the aging causes discussed above for different sensors and propose several potential solutions.

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Table 1. Types of mechanical sensors

Sensor Types	Factors affecting the aging process	Mode of aging (bias principle)	Characterization of aging (bias phenomenon)	Protective measures
Piezoresistive	Temperature, PN junction leakage current, internal stress, shock vibration	Leakage current rises with temperature, structural damage to piezoresistor material	Zero and sensitivity drift, loss of varistor characteristics	Thermal shielding and improved heat dissipation, add buffer structure
Piezoelectric	Temperature, humidity, shock and vibration	Disordered or depolarized domains in piezoelectric materials, surface defects interfering with carrier motion, loose electrodes	Dielectric constant degradation, sensitivity drift, sensor failure	Doping and defect engineering, heat treatment, sealing protection
Capacitance	Temperature, humidity, electromagnetic radiation, cyclic stresses	Dielectric thermal expansion, series capacitance due to liquid water, parasitic capacitance introduced by external objects, coupling to external electromagnetic fields, material fatigue	Zero and sensitivity drift, signal noise	Thermal shielding and sealing, electromagnetic and structural improvements, use of filtering algorithms
Optical	Temperature, humidity, surface defects	Waveguide deformation due to thermal expansion alters the optical path, defects form on the surface of the photodiode	Zero and sensitivity drift, degradation of signal-to-noise ratio of optoelectronic components	Heat shielding, hermetic protection
Electromagnetic	Electromagnetic radiation, shock and vibration	Electromagnetic radiation introduces extraneous signals, structural deformation	Measurement noise, zero and sensitivity drift	Electromagnetic shielding
Frictional Electricity	Temperature, humidity, shock vibration	Temperature promotes loss of surface charge from hot electron emission, temperature accelerates material aging, water vapor promotes charge dissipation	Reduced output power, zero and sensitivity drift	Heat shielding, sealing protection, the use of rational structure

Based on the information in Table 1, the common aging causes and corresponding solutions can be summarized as follows:

3.1. Temperature

Previous studies have clearly shown that abnormal temperatures are a common factor accelerating the aging of mechanical sensors. High temperatures in the operating environment can degrade the performance of core sensor materials or damage the material structure. To mitigate these effects, measures such as adding thermal insulation layers and improving heat dissipation conditions can be adopted.

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3.2. Humidity

In addition to temperature, humidity is another critical factor that adversely affects several types of mechanical sensors relying primarily on electrical signals. For example, mechanical sensors used in health monitoring are subject to influences such as sweat during operation. High environmental humidity can not only cause malfunction or short circuits in certain circuit components but also exacerbate the impact of surface defects in sensor materials.

3.3. Electromagnetic radiation

Electromagnetic radiation is also a common influencing factor in industrial production environments. To mitigate such interference, sensors can be protected through electromagnetic shielding.

3.4. External forces

As mechanical sensors inherently measure forces, the vast majority of sensors used in industrial and daily life applications inevitably experience an extremely large number of load cycles during operation. This implies that material changes over the sensor's entire lifecycle must be considered as part of its aging process [37]. Additionally, accidental external impacts and common vibrations in the working environment are also frequent contributors to sensor aging.

3.5. Possible solutions

In summary, for most mechanical sensors, it is feasible to reduce aging effects by using materials with superior performance or optimizing structural design. However, a more practical approach involves applying filtering and noise reduction algorithms or implementing real-time compensation of aging-induced drift signals based on early-stage monitoring data [24,41,42].

Furthermore, when cost and environmental conditions permit, periodic replacement of mechanical sensors with new units remains the most effective solution.

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