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AUTOMOBILE STRUCTURAL HEALTH MONITORING USING PIEZOELECTRIC SENSORS

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Abstract

Structural health monitoring (SHM) of automobiles is important to detect damage at an early stage and prevent failures. This paper provides a comprehensive review of using piezoelectric sensors for SHM in automobiles. Firstly common damage types in automobile structures are introduced. Thereafter, the operating principles, modeling, and application of piezoelectric sensors for damage detection are reviewed. Different sensor configurations such as piezoelectric ceramics, piezoelectric wafer active sensors (PWAS), and piezoelectric fiber composites are evaluated. The use of piezoelectric sensors with other SHM techniques like acoustic emission and guided waves is also discussed. Finally, the current challenges and future research directions in this field, including optimizing sensor placement, environmental temperature effects, and integrated SHM systems are summarized. The tables provided give an overview of typical applications, advantages and limitations of different piezoelectric sensors, and comparisons with other popular SHM techniques. This review covers the latest progress and demonstrates the effectiveness of piezoelectric sensors for automobile SHM.

Keywords: Structural Health Monitoring; Automobiles; Piezoelectric Sensors; Damage Detection; Sensor Configurations

1.0 INTRODUCTION

Structural health monitoring (SHM) is essential for improving automobile safety and reducing maintenance costs [1–3]. SHM aims to monitor the condition of a structure by detecting the presence of damage at an early stage [4]. If undetected, damage can progress and lead to catastrophic failures in automobiles [5]. Common damage types include cracks, corrosion, delamination, loose joints, etc. [2,6]. Effective SHM enables timely repairs and prevention of such failures. Various SHM techniques have been developed over the years for applications in automobiles [2,7]. These include both local methods like ultrasound and vibration analysis as well as global approaches using modal analysis and dynamic strain measurements [8]. Of the various SHM techniques, the use of piezoelectric sensors has attracted tremendous research over the past two decades [9–12]. Piezoelectric sensors offer simple working principles, economical configurations, and possibility of integration within automobile structures [13–15]. This makes them highly suitable for SHM in comparison to conventional resistance strain gauges [16]. In this paper, we review piezoelectric sensors for SHM of automobile structures. Section 2 introduces the common damage types needing detection in automobiles. Section 3 discusses piezoelectricity fundamentals and damage detection approaches using piezoelectric sensors. Configurations like piezoceramics, piezoelectric wafer active sensors (PWAS), and piezoelectric fiber composites are reviewed in Section 4. Important considerations in sensor modeling and bonding to the host structure are also covered. Section5 evaluates the performance of piezoelectric sensors for typical automobile materials and damage types. Integration with other SHM techniques like acoustic emission and guided ultrasonic waves is elaborated in Section 6. Section 6 finally concludes with a discussion on current challenges and outlook.

2.0 TYPICAL DAMAGE IN AUTOMOBILE STRUCTURES

Automobile structures experience various types of damage during operation and need to be monitored [17]. Axle and suspension damage reduce ride quality while issues in the chassis and body affect overall integrity [18]. Common damage modes are summarized below [2,6]:

Cracks: One of the most dangerous forms of damage. Cracks originate from stress concentration regions and can propagate rapidly under fatigue loading. Multi-site damage with several small fatigue cracks often occurs in automobile structures [19].

Corrosion: Automotive steel is prone to both general surface corrosion as well as localized galvanic and crevice corrosion [20]. This causes material loss and reduces load carrying capacity.

Delamination: Delamination involves separation of composite laminate layers and binding matrix. This is prevalent in glass and carbon fiber reinforced polymer (GFRP/CFRP) automobile parts [21]. Loose joints/connections: Joints and welds can become loose over time due to vibrations and impact loads. This changes load transfer paths in the structure [2].

Table 1 gives typical locations and types of damage occurring in automobile bodies, chassis systems, and suspensions [2,6]. Reliable SHM is necessary to detect the onset of such damage during operation itself. Piezoelectric sensors are well-suited for this as discussed in the following sections.

Table 1. Typical Locations and Modes of Damage in Automobiles

Components of Automobile	Damage type	Location
Body	Cracks, Loose Joints	Door Welds, Roof Joints
	Corrosion	Floor Panel, Side Rails
	Delamination	Hood, trunk Lids (Composite)
Chassis	Loose Joints	Frame Joints
	Cracks (Fatigue)	Wheel Arches
Suspension	Cracks	Control Arms
	Loose Joints	Shock absorber Mount
	Wear Cracks	Universal Joints

3.0 PIEZOELECTRIC SENSING FUNDAMENTALS FOR SHM

3.1. Piezoelectric Effect for Sensing

Piezoelectric materials generate electric charge under mechanical strain, known as the direct piezoelectric effect [22,23].

The constitutive equations relating strain S_{ij}, stress T_{ij} and electric field E_k are:

$S_{ij}=sE_{ijkg}T_{kg}+d_{mi}E_m$ (1)

Where, S_{ij}: Components of the strain tensor

T_{kg}: Components of the stress tensor

E_{ijkg}: Fourth-order tensor representing the elastic constants relating stress and strain (the elasticity tensor)

E_m: Components of the electric field vector

S: Scalar parameter relating stress and strain under the influence of the electric field.

d_{mi}: Components of the piezoelectric tensor, relating strain to the electric field.

$D_i = d_{mi}S_{mi} + \varepsilon T_{ik}E_k$ (2)

Where,

D_i: Components of the electric displacement vector

S_{mi}: Components of the strain tensor

T_{ik}: Components of the stress tensor

E_k: Components of the electric field vector

d_{mi}: Components of the piezoelectric tensor, relating strain to electric displacement.

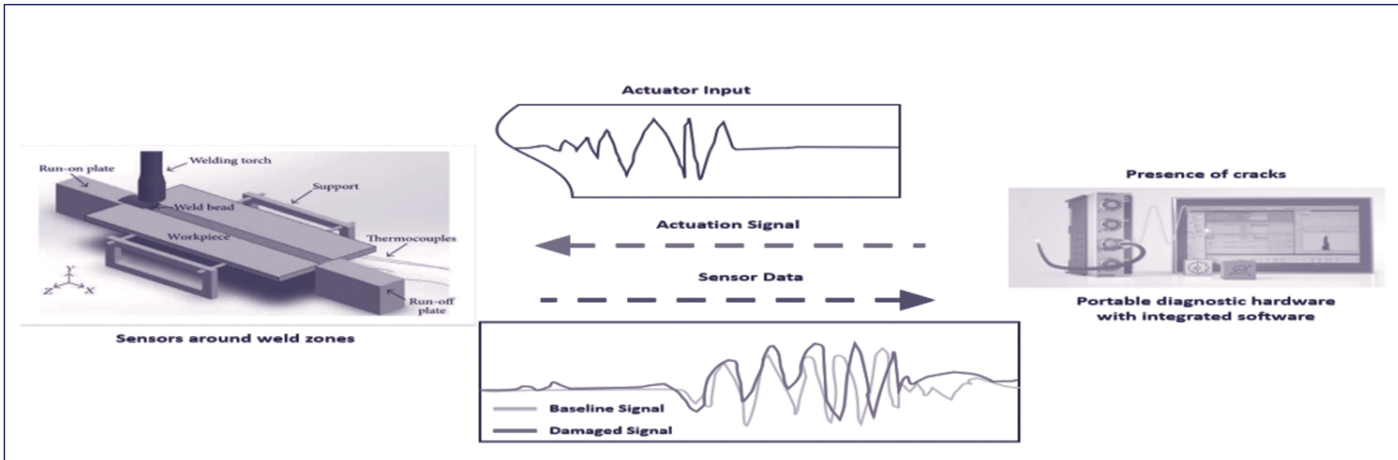
ε: Permittivity of the material, often represented as $\varepsilon_0$times the permittivity tensor ε_{ik}, relating electric field to electric displacement.

Eq. (1) shows that an applied stress generates charge proportional to the piezoelectric strain coefficient d_m. Thus, damage inducing strain in a structure attached to piezoelectric sensors can be detected from the electric response. Common piezoelectric materials used include Lead Zirconate Titanate (PZT) ceramics as well as polymeric Polyvinylidene Difluoride (PVDF) films.

3.2. Guided Waves and Acoustic Emission

Dynamic high frequency stress waves are an effective means for damage detection and location in plate-like structures [24–26]. When generated intentionally for interrogation, they are called guided ultrasonic waves. Stress waves produced by damage events like crack growth are referred to as acoustic emission. Properties like propagation distance, mode shapes, frequency range, and excitation methods make guided waves optimal for most applications [27–29]. This approach using piezoelectric wafer active sensors (PWAS) and acoustic emission is illustrated in Figure 1 [30]. The sensors detect acoustic emission from damage like crack growth as well as actively interrogate the structure using guided waves. Cracks and corrosion induce reflections and mode conversions of the traveling ultrasonic waves, allowing damage severity quantification [25,31].

Figure 1. Piezoelectric sensor detection of acoustic emission and ultrasonic guided waves for structural health monitoring. ***(Courtesy: Havit Steel, Bekhof)***



3.3. Resonance Methods

The mechanical resonance frequencies of a structure depend on physical properties like mass, stiffness and boundary conditions. Damage causes local reductions in stiffness, leading to detectable shifts in these frequencies [32]. Resonance methods are hence simple yet effective for damage detection. The admittance signature acquired by the piezoelectric sensor itself can indicate resonance frequency changes [33]. Driving a structure at resonance using piezoelectric actuation creates global vibrations that are highly sensitive to minor damage [34]. Monitoring the structural response or piezo sensor output reveals stiffness loss due to damage [35].

4.0 PIEZOELECTRIC SENSOR CONFIGURATIONS AND MODELING

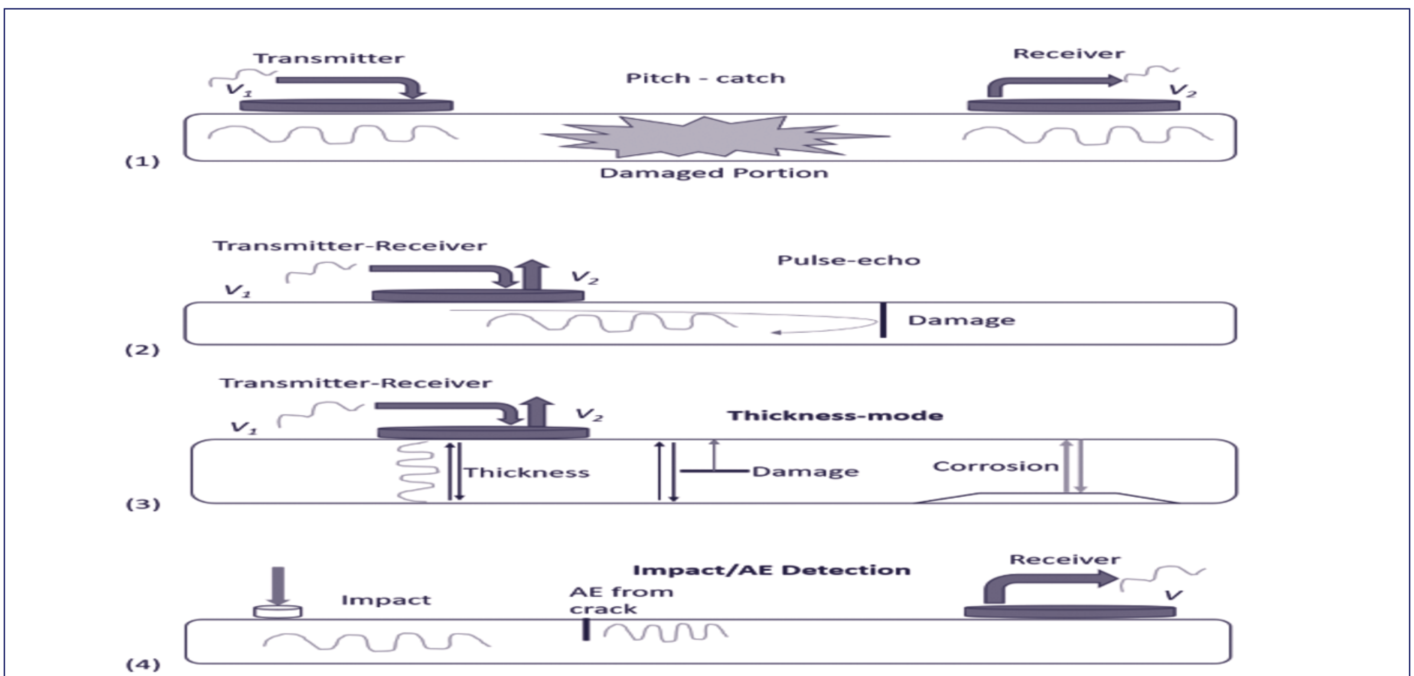
Various piezoelectric sensor configurations used for SHM are discussed below:

4.1. Monolithic Piezoceramics

Bulk piezoceramic wafers like PZT provide high piezoelectric strain coefficients for dynamic sensing

[36]. But their brittle nature necessitates careful handling and installation using adhesives [16]. Representing the ceramic wafer and substrate as an electric circuit gives an electromechanical model for analysis [37]. The substrate mechanics is modeled as an impedance Zs with series/parallel capacitance Cp/Cs representing dielectric and mechanical coupling [38]. Equivalent circuit analysis allows sensor optimization and bonding design [39].

Figure 2. Application of piezoelectric wafer active sensors (PWAS) as traveling wave transducers for detection of damage: (a) pitch-catch; (b) pulse-echo; (c) thickness mode; (d) Impacts and acoustic emission detection (AE).*(Courtesy: Connor Griffin and Victor Giurgiutiu)*



4.2. Piezoelectric Wafer Active Sensors (PWAS)

PWAS provide a durable thin wafer encapsulated in protective polymer with electrodes on both sides [40]. Strong interface composites transmit strain to the piezo material for dynamic sensing [41]. Electromechanical coupling can be mathematically expressed using modal electromechanical impedance obtained from eigen analysis [42]. Broadband vibration excitation reveals structural resonance shifts from damage [43]. PWAS have emerged as a versatile conformal SHM technology due to light weight, low cost and high bandwidth beyond 100 kHz [44]. Their working principle is shown in Figure 2.

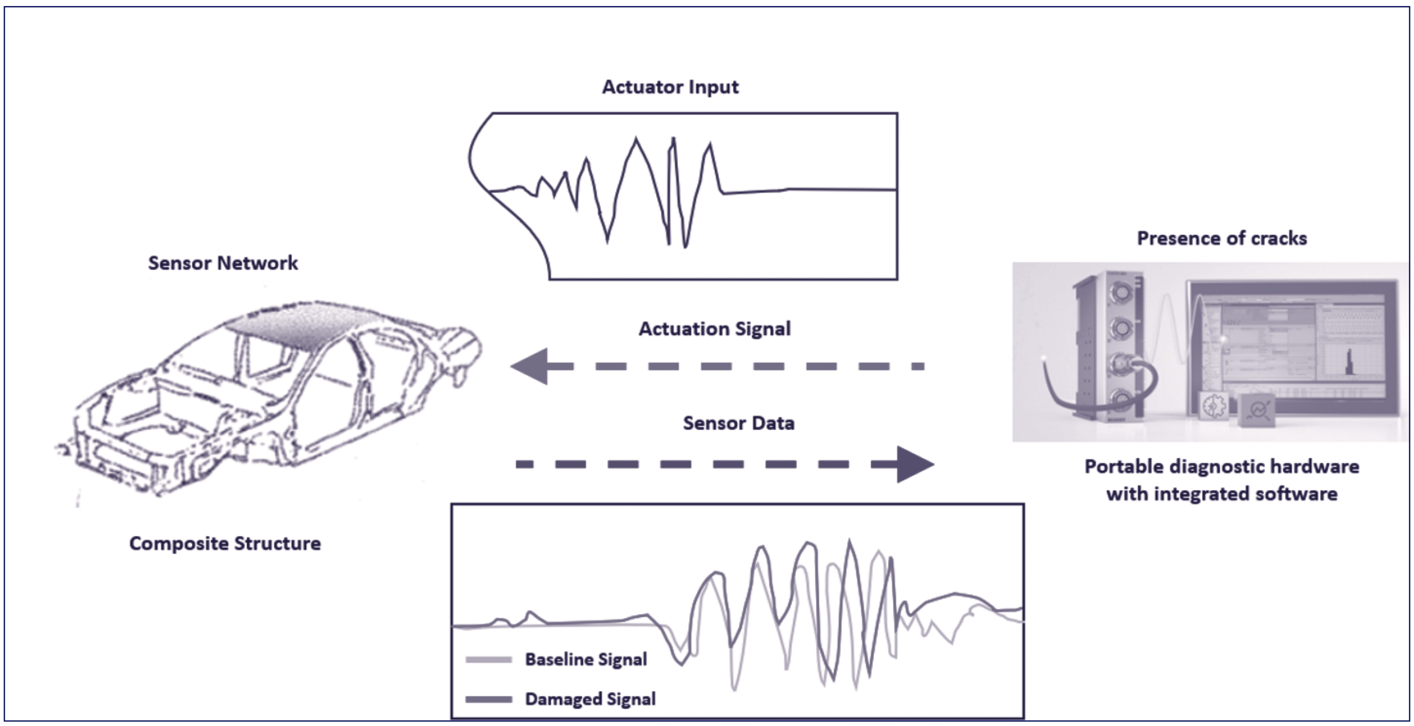
4.3. Macro Fiber Composites (MFC)

MFC consists of rectangular piezoceramic rods sandwiched between adhesive polymer layers and electrodes. The polymer matrix makes it durable and enhances mechanical strain transfer [45]. Interdigitated electrodes allow MFC to be oriented along optimal sensing direction [46]. MFC can be surface mounted or bonded within composites for both sensing and actuation [47]. Electromechanical dynamics are simulated using a layered plate model considering stress, strain and electric variables [48]. High conformability suits MFC for complex curved geometries like cylinders [49].

4.4. Piezoelectric Fiber Composites

Piezoelectric fiber composites integrate thin piezoceramic fibers or PVDF polymer into woven glass/carbon plies [50,51]. The composite laminate thus has self-sensing ability in addition to structural strength. 1-3 piezo composites with continuous polymer and discontinuous transverse rods provide flexibility and prevent sensor damage [52]. Stiffness matrix based multilayer models have been formulated for predicting the sensor response [53]. Such composites demonstrate the feasibility of integrated SHM solutions [54]. The piezo fibers detect damage induced strain with applications ranging from storage tanks to aerospace components [55,56]. A SHM sandwich structure is illustrated with integrated piezoelectric fiber sensors in the composite face sheets and foam core [57]. Figure 3 shows typical such configurations suitable for composite auto parts like body panels and spoilers [58]. The main advantage compared to surface bonded sensors is the protection for the fragile piezoelectric material besides structural load sharing [14]. Polymer based piezo fibers have emerged due to flexibility, damage tolerance and high temperature survival beyond 150 °C [59].

Figure 3. Automotive SHM applications using integrated piezoelectric fiber sensors. ***(Courtesy: Webasto, and Hu Sun)***



4.5. Sensor Installation and Bonding

The sensor-host structure interface plays a crucial role in transmission of damage induced strain [60]. Robust compression loading minimizes shear stress and slipping [61]. Cyanoacrylate adhesives provide suitable bonding for unpredictable vehicle environments [62]. Epoxy bonding allows durability up to 150 °C for engine monitoring [63]. Spot welding gives reliable localized attachment similar to resistance strain gauges [64]. Proper sensor boundaries should be maintained to avoid stress concentration and load carrying [65]. Electromechanical impedance signatures assess debonding or poor installation [66].

4.6 Performance Evaluation and Applications

Piezoelectric sensors have shown excellent capability for damage detection across common materials used in automobile structures. Fatigue crack identification under cyclic loading has been demonstrated on alloy steel and aluminum samples using sub-millimeter MFC patches [67]. Crack initiation and growth up to failure was clearly identified from the change in electromechanical admittance signatures. Corrosion damage in steel plates has been located with guided waves using low-cost piezoelectric diaphragms [68]. Corrosion pits of 5% cross section loss were reliably detected proving field deployability.

Automotive grade composites like fiberglass, Kevlar and carbon fiber reinforced polymers have gained adoption for structural parts. Delamination as a critical failure mode has been investigated extensively for these materials using piezoelectric sensors. Glass fiber laminates with embedded MFC were able to indicate delamination length through pulse echo tests [69]. Stacked Kevlar laminates monitored using piezoceramic acoustic emission sensors successfully differentiated delamination from transverse cracking [70]. Carbon fiber panels instrumented with wafer sensors have localized delamination area under fatigue bending through modulation of guided wave propagation [71].

Suspension components undergo significant dynamic loading necessitating frequent inspection. Hollow steel struts in suspension arms were interrogated using traveling waves from surface mounted ceramic patches [72]. The time-of-flight change and mode conversion loss reliably identified 1 mm cracks at 150 kHz excitation. For composite suspension arms, multidirectional MFC sensors were proven effective in detecting crack orientation [73]. Joints and fittings like ball bearings have also been evaluated with acoustic emission monitoring via piezoceramics indicating subsurface raceway defects [74]. Table 2 summarizes typical applications and feasibility of piezoelectric sensors for SHM of major automobile structural components.

Table 2. Overview of Piezoelectric Sensors for Monitoring Different Automobile Components.

Structural Components of Automobile	Type of Sensor Used	Type of Damage	Performance
Aluminum Wheels	MFC	Cracks (Fatigue)	Effective
Composite Body Panels	Piezo Fibers	Delamination	Highly Effective
Drivetrain	MFC	Wear, Pitting	Complex
Engine (Steel)	Piezo Fibers (High Temperature)	Cracks, Leakage	Active research
Shock Absorbers (Joints)	PWAS	Loose Fittings	Feasible
Steel Chassis Frame	PWAS	Cracks, Loose Joints	Encouraging
Suspension Arms (Steel/ Composite)	Piezoceramics	Cracks, Wear	Effective

5. PERFORMANCE EVALUATION

The installed sensors will do the data acquisition, signal processing, fault detection, evaluation and reporting. The elaborate details are given here.

5.1. Data Acquisition

This is accomplished by choosing the hardware and software capable of capturing sensor signals with sufficient resolution and sampling frequency. The sampling rates, filtering options and trigger conditions based on the expected frequency range and dynamics of structural responses need to be set. Synchronize the data acquisition with vehicle operation or external triggers to capture relevant events and correlate sensor data with operational conditions. Employ redundant sensors or multiple channels to ensure data integrity and minimize the risk of data loss or sensor failure during monitoring.

5.2. Sensor Processing

As a pre-process, apply filtering techniques (e.g., low-pass, band-pass filters) to remove noise and artifacts from sensor signals. Identify relevant features from sensor data using time-domain, frequency-domain, or time-frequency analysis methods. Design algorithms to detect deviations from normal operating conditions based on predefined thresholds or statistical models. Implement efficient signal processing algorithms suitable for real-time monitoring applications while minimizing computational overhead.

5.3 Fault Detection

Establish criteria for identifying structural faults or anomalies based on sensor data characteristics (e.g., amplitude, frequency, temporal patterns). Utilize supervised or unsupervised learning techniques to train models for fault detection using labeled or unlabeled datasets. Evaluate the performance of fault detection algorithms using simulated faults, laboratory tests, or field measurements under varying operating conditions. Integrate fault detection results into decision support systems to provide actionable insights for maintenance and repair decisions.

5.4. Performance Evaluation

Specify quantitative metrics (e.g., accuracy, false alarm rate, detection time) for evaluating the performance of the SHM system. Perform validation tests under controlled conditions to assess the system's capability to detect known faults and quantify its reliability. Compare the performance of the SHM system with traditional inspection methods (e.g., visual inspection, non-destructive testing) to evaluate its effectiveness and efficiency. Monitor the SHM system over extended periods to assess its long-term reliability, durability, and maintainability in real-world operating environments.

5.5. Documentation and Reporting

Maintain detailed documentation of the evaluation procedure, including sensor specification, calibration records, data acquisition settings, and signal processing algorithms. Prepare reports summarizing the evaluation process, experimental results, performance metrics, and recommendations for system improvement optimization. Disseminate research findings through technical papers, conference presentations, or industry workshops to contribute to the broader knowledge and adoption of SHM technologies in automotive engineering.

6. INTEGRATION WITH COMPLEMENTARY SHM TECHNIQUES

While piezoelectric sensors have shown excellent standalone capability for damage detection, their combination with complementary techniques promises even greater implementation feasibility across automobile platforms. Important synergistic approaches are discussed below:

6.1. Electromechanical Impedance Method

This structural interrogation approach characterizes local regions by driving surface mounted piezo transducers around resonance [75]. The measured electrical impedance indicates interacting mechanical impedance which changes due to damage. Impedance signatures reliably detect loose bolts and cracks across metallic structures [76]. Parameter extraction using statistical tools offers further sensitivity refinement [77].

6.2. Acoustic Emission Monitoring

This passive technique relies on detecting stress waves released by damage events using piezoelectric sensors [78]. Source characterization through multiple sensors allows crack localization [79]. Signal processing reveals damage severity from parameters like frequency content [80]. Low cost piezo paint and tape sensors facilitate large area deployment [81].

6.3. Ultrasonic Guided Waves

Tunable narrowband excitation coupled with wideband sensing provides versatility for composites [82]. Wave modulation confirms damage without baseline data requirements [83]. Tomography and imaging algorithms give damage maps for asset life management [84,85]. Energy harvesting versions directly power such wireless sensor nodes [86]. Guided waves thus leverage piezoelectric transducer capability for autonomous inspection. The synergistic combinations for damage detection in automobiles enables comprehensive SHM to be realized through documented test cases on complex structures [87–89]. Industry 4.0 integration further helps predictive maintenance using cloud analytics and digital twin correlations [90]. Table 3 summarizes the complementary advantages offered by these techniques versus standalone piezoelectric sensors.

Table 3. Comparison of Piezoelectric Sensors with Complementary Structural Health Monitoring (SHM) Techniques for Damage Detection

Procedure	Principle	Advantages	Disadvantages
Piezoelectric Sensors	Strain Induced by Damage measured through Passive Sensing	Simple, Direct	A Priori Baseline Data Often Required.
Electromechanical Impedance	Tracking of Resonance Signature	High Sensitivity	Only Detects Local Damage
Acoustic Emission	Signals Emitted from Damage Events	Collected Data from damage Timing	Complex data can be processed
Guided Ultrasonic Waves	Active Interrogation	Long Range Detection	Analysis is Complex

7. CONCLUSION

Piezoelectric sensors present versatile possibilities for condition monitoring and damage detection across metallic and composite automobile structures. Their capability to detect typical damage modes like cracks, corrosion and delamination has been well established through fundamental experiments and field studies. Performance is encouraging for chassis, suspension and engine components with the possibility for wireless data aggregation. Future work should address optimal sensor positioning and array layouts using topological factors besides expanding the defect typologies. Temperature resistance necessitates expansion beyond the current 100–150 °C range for powertrain monitoring. Integration with antenna-based wireless interrogation is another key development area. Online SHM with automated interpretation of sensor data will enable cost-effective and reliable prognosis frameworks. Additional civil structures and transportation applications beyond automobiles including aircraft and ships provide major opportunities for piezoelectric sensor deployment. Addressing present limitations and emerging embeddable configurations will enable such smart multifunctional systems, contributing towards safer and efficient mobility infrastructure.

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