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Review

A Review of Piezoelectric Material-Based Structural Control and Health Monitoring Techniques for Engineering Structures: Challenges and Opportunities

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Abstract: With the breadth of applications and analysis performed over the last few decades, it would not be an exaggeration to call piezoelectric materials "the top of the crop" of smart materials. Piezoelectric materials have emerged as the most researched materials for practical applications among the numerous smart materials. They owe it to a few main reasons, including low cost, high bandwidth of service, availability in a variety of formats, and ease of handling and execution. Several authors have used piezoelectric materials as sensors and actuators to effectively control structural vibrations, noise, and active control, as well as for structural health monitoring, over the last three decades. These studies cover a wide range of engineering disciplines, from vast space systems to aerospace, automotive, civil, and biomedical engineering. Therefore, in this review, a study has been reported on piezoelectric materials and their advantages in engineering fields with fundamental modeling and applications. Next, the new approaches and hypotheses suggested by different scholars are also explored for control/repair methods and the structural health monitoring of engineering structures. Lastly, the challenges and opportunities has been discussed based on the exhaustive literature studies for future work. As a result, this review can serve as a guideline for the researchers who want to use piezoelectric materials for engineering structures.

Keywords: piezoelectric material; vibration control; noise control; active control; damage structure; SHM

1. Introduction

In the direction of smart material applications in engineering systems, various efforts were made. These intelligent materials have certain properties that can be desirably altered by varying stress, temperature, and a magnetic or electric field, which serves as an external stimulus in a controlled environment. A *smart material* is mainly divided into two types, "piezoelectric transducer" and "shape memory alloys", and these types of materials are more frequently used in various fields. Piezoelectric material transducers have both sensors as well as actuator functionality [1]. The piezoelectric materials have become popular over the last three decades due to their electromechanical effects and versatile applications. The emphasis has shifted to piezoelectric-based methods due to their implications, which include operational cost reductions in preservation as well as an improvement in the structure's life cycle. The piezoelectric materials have been utilized for many purposes in engineering structures. In the event of the initiation of cracks/damages, any type of structure requires high maintenance of safety or can result in the replacement of the whole structure, and these damages are mostly due to fatigue/corrosion. Such cases have been solved by the application of piezoelectric materials [2–10]. Indeed, in the last decade, piezoelectric materials were utilized for the control/repair of structures such as aerospace, concretes, and photovoltaic solar panels.

On the other hand, the use of piezoelectric-based structural health monitoring (SHM) has assisted in the transformation of the industry for various engineering aspects, while the electromechanical process, a relatively recent non-destructive research tool, has been studied for more than two decades and there are still a number of issues that must be resolved before it can be extended to actual structures. The methodology requires the use of a single piezoelectric for exciting and detecting the host structure and can lead to the advancement of one of the most efficient SHM systems. Moreover, many researchers are investigating the electromechanical impedance (EMI) technique for SHM via experimental and computational standpoints. Structural disruption, sensor/actuator faults, and delamination can all be detected using the EMI technique. The sensor's self-detection is important because it can lead to a defective diagnostic, causing the device to malfunction. As a result, several researchers in the SHM group are focusing on sensor self-diagnosis. Although the EMI analysis is complicated, it can be carried out by breaking down the structural loss into actual and theoretical impedance components.

In this review, literature has been carried out based on the control of damaged structures (vibration, noise, and active), the SHM of engineering structures. The control of damaged structures using piezoelectric materials is a highly developed research concept in current industries, particularly in the aerospace industries. The SHM is the most useful character of piezoelectric material for monitoring any type of structure; hence, there are a number of studies that have reported on this. The next two sections are about piezoelectric materials and their modeling. Section 3 expresses the control of structures and Section 4 extracted some of the studies of SHM to cover the piezoelectric applications in recent years. Section 5 elucidates the challenges and opportunities in this field and is particularly related to the present review contents. Finally, a conclusion has been constructed based on the current review work.

2. Piezoelectric Materials

The direct piezoelectric effect is the capability of piezoelectric materials to create an electric field under the influence of mechanical stress. This property of the piezoelectric materials is utilized for the generation of electrical energy. The reciprocal of the direct piezoelectric effect is the inverse piezoelectric effect in which mechanical strain is developed in response to the electric field. These effects are strongly dependent on the crystal orientation with respect to the strain or electric field [11–16]. The direct effect makes it possible to use them as sensors, and the converse effect as actuators (Figure 1). The designed structures constructed using piezoelectric materials can be bent, expanded, or contracted upon the application of voltage, and they can be used for sensing and actuating [17] purposes and for easy control [18]. Piezoelectric patches (or films) are thin ceramic strips that are either intended to be bonded to the substructure surface or to be inserted within the structure. The stacks instead are built by piling up multiple piezoelectric layers of alternating polarity [19]. The piezoelectric materials are widely used in valves, micropumps, earphones and speakers, ultrasonic cleaners, emulsifiers, and sonic transducers.

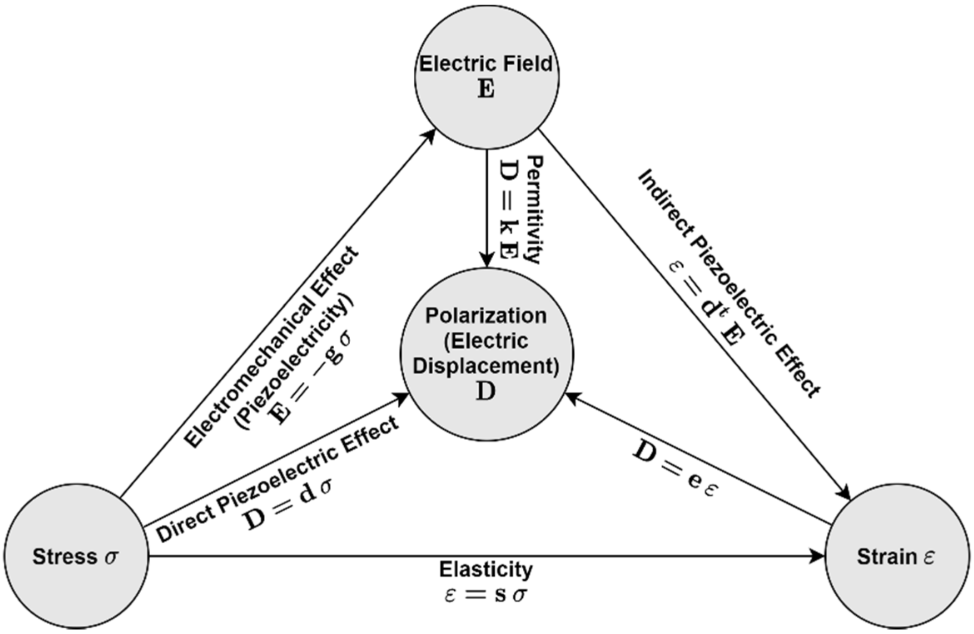

Figure 1. Effect of Piezoelectric material [15]. Reprinted under the Creative Commons (CC) License (CC BY 4.0).

In addition to piezoelectric ceramics, piezoelectric polymers are another group of piezoelectric materials that have found widespread use. Polyvinyl fluoride (PVDF) is versatile and light in weight in comparison to piezoelectric ceramics. Because of this, thin films of any desired form can be drawn into them, giving them an advantage over piezoceramics in various applications involving complex designs of sensors or actuators. Besides being versatile and lightweight, however, they have lower electromechanical coupling compared to piezoelectric ceramics, and the other characteristics that make the piezoelectric polymers attractive are their low electrical permittivity, low acoustic impedance, high voltage sensitivity, and relatively lower cost. An updated overview of the applications of piezoelectric polymers in touch devices, pyroelectric infrared sensors, property measurement with photopyroelectric spectroscopy, and shock sensors can be observed in the article by Lang and Muensit [20].

2.1. Piezoelectric–Mechanical Constitutive Equations

In piezoelectric ceramics, nonlinear dielectric, elastic and piezoelectric relationships were well established in piezoelectric constitution equations as well as Preisach-type models, which were employed to define the hysteretic path-dependent strain–field relationship in piezoelectric actuator models [21]. Generally, the relation for the constitutive equation for piezoelectric materials is written as:

$$S = c^E \cdot T + [d]^t \cdot E \tag{1}$$

$$D = d \cdot T + \varepsilon^T \cdot E \tag{2}$$

where T is the constant stress, E is the constant field, C is the stiffness coefficient, D is the constant electrical displacement, S is the constant strain, ε^T is the dielectric permittivity, and d is the piezoelectric constant matrices. The superscript E and t indicate a constant electric field and charting time, respectively, for the compliance matrix that is evaluated. These matrix relations are generally used for modeling finite element (FE) analysis. Only some of the relationships are typically useful for theoretical methods to simplify the problem further [22].

2.2. Reduced-Order Modal Equations

Reduced-ordered modal equations from the piezoelectric constitution equation can be governed for the modal coordination system with the mode of the superposition process. In addition, the FE nodal displacement vector can transfer the modal coordinate vector with the used modal matrix system. With this, there is a possibility to express the approximate relation of generalized nodal displacement vector {d}:

$$\{\mathrm{d}\} \approx \sum_{\mathrm{i}=1}^{\mathrm{r}} \varnothing_{\mathrm{i}} \mathrm{q}_{\mathrm{i}} = [\varnothing]\{\mathrm{q}\} \tag{3}$$

where

$$[\varnothing] = [\varnothing_1, \ldots, \varnothing_n](n < r) \tag{4}$$

where $\{\mathrm{q}\}$ is the coordinate vector (modal), in which n order is a time-dependent vector, and n variable represents the variation of the modal in a form of numbers for preserved/controlled.

After being introduced, the damping of the feedback control system for a reduced-order modal equation for a linear de-coupled form is as follows:

$$[\overline{\mathrm{M}}]\{\ddot{\mathrm{q}}\} + [\overline{\mathrm{C}}_{\mathrm{d}}]\{\dot{\mathrm{q}}\} + [\overline{\mathrm{K}}]\{\mathrm{q}\} = \{\overline{\mathrm{F}}\} + [\overline{\mathrm{K}}_{\mathrm{A}}]\{\mathrm{u_a}\} \tag{5}$$

Here, $[\overline{\mathrm{M}}]$ is the modal mass and it is expressed as $[\overline{\mathrm{M}}] = [\varnothing]^{\mathrm{T}}\{\mathrm{F}\}$, $\{\mathrm{u_a}\}$ is the applied voltage of piezoelectric actuators (input vector control), and $[\overline{\mathrm{K}}_{\mathrm{A}}]\{\mathrm{u_a}\} = [\varnothing]^{\mathrm{T}}\{\mathrm{F_P}\}$, where $[\overline{\mathrm{K}}_{\mathrm{A}}]$ is the stiffness matrix of the modal actuator or control input effect matrix.

Concerning mass, normalize the modal matrix $[\varnothing]$ and a structural damping coefficient ζ_{i} $(\mathrm{i} = 1, \ldots, \mathrm{r})$ is assumed; then, the modal system becomes:

$$\{\ddot{\mathrm{q}}\} + \mathrm{diag}\,[2\zeta_{\mathrm{i}}\omega_{\mathrm{i}}]\{\dot{\mathrm{q}}\} + \mathrm{diag}\left[\omega_{\mathrm{i}}^2\right]\{\mathrm{q}\} = \{\overline{\mathrm{F}}\} + \left[\overline{\mathrm{K}}_{\mathrm{A}}\right]\{\mathrm{u_a}\} \tag{6}$$

where ω_{i} is the natural frequency and a mode form vector that corresponds to each mode is $\varnothing_{\mathrm{i}}$ $(\mathrm{i} = 1, \ldots, \mathrm{r})$.

2.3. Piezoelectric Material Type-Based Investigation and Issues

Lee et al. [23] prepared specimens of lead meta niobate (LMN) [24] from the commercially available piezoelectric transducer, and these were polled by the manufacturer for use in the transducers [25]. The damping of structural vibration LMN was employed because that material tends to stick. It has been observed that the piezoelectric effect is mostly in the form of artificial piezoelectric material and advantageous features of generating electricity, and it can effectively repair the crack and can carry out SHM. Mohammad et al. [26] studied the ceramics containing 1% of SrTiO3 (SPN) with orthorhombic and tetragonal structures. These ceramics simultaneously exhibited a maximum piezoelectric constant. Because of their denser and similar composition to stoichiometry, microwave sintered ceramics showed a higher piezoelectric constant in comparison to traditional sintered ones. Arian et al. [27] studied their usage in multi-layer ceramic capacitors, lead-based perovskite materials (MLCCs). There are benefits to these materials over traditional materials such as barium titanite. Due to the diffuse phase transition, they show a very large dielectric. The best results were obtained by the stoichiometric lead magnesium niobate (PMN) [28] with a lower sintering temperature of about 900 °C and a relative dielectric constant of 10,000 at room temperature. The piezoelectric properties were defined in the constitutive equations, assuming that the total strain in the transducer is the sum of the mechanical strain caused by the mechanical stress and the controllable actuation strain induced by the electrical voltage applied. A study carried out by Pasquali et al. [29] presented the nonlinear piezoelectric plate model that was capable of accurately demonstrating the direct and convergent piezoelectric effect. The starting point of the nonlinear piezoelectric plate model for full electromechanical coupling may be an empirical expression of electrical potential. Some of the issues/requirements in piezoelectric materials that can be considered an important aspect while using the structures are as follows [30]:

- In comparison to the host structure, the PZT transducer should be non-reactive and have marginal stiffness and strength. It should also be protected from environmental factors such as humidity, precipitation, and temperature.
- The frequency spectrum of excitation determines the sensing region of the PZT transducer. A wider sensing domain is covered by frequencies below 30 kHz. High-frequency EMI models are only applicable to a small region.
- An arrangement has parts that are weak or essential that need more effort than others. High-stress fields, corrosive environment areas, and so on, must all be monitored closely. The length, distance, and thickness of the PZT actuation are all three directions. As a result, a detailed estimate of the PZT-sensing region must be determined using these three types of actuations, based on the geometry and material properties of the host structure.
- In the absence of damages, PZT transducers are effective at measuring the loading on a structure, or vice versa. The study on PZT-based EMI for load applications is largely limited to 1D structures, but [31] shows some work on 2D, 3D, and complex structures.
- To track any structure using EMI-based SHM, the current usual practice is to first acquire a baseline signature. This is then compared to later levels of the structure's EM admittance signatures to see if the structure has any flaws. It is very difficult to achieve the no-damage baseline signature for older current systems, making comparisons with later stage signatures almost impossible. As a result, any signature obtained from any structure at any point in time should provide overt or implied knowledge about the structure.
- As the embedded or surface bonded PZT transducer is excited, the 'structural responses' are extracted and expressed as conductance and susceptibility signatures. The structural reaction varies with the frequency of excitation. The effectiveness of any non-parametric index is determined by its ability to detect harm using all modified peaks.
- Ultrasonic technology, acoustic absorption, magnetic field analysis, global structural reaction analysis, and visual inspection techniques have also been proven to be useful at identifying damage early on. Regardless of their usefulness, both of these approaches should be used in conjunction with the EMI technique.

3. Structural Control Using Piezoelectric Material

Control of structures is a study in which the piezoelectric materials have been utilized for various purposes. Due to the versatile application, the PZT transducer can control metallic and non-metallic structural components, and this section reviews the piezoelectric materials as the main object to control structural component's vibration, noise, and activity. Furthermore, this section summarizes the methodologies that were used to achieve the goals.

3.1. Vibration Control

This concept was first presented by [32], proposing the use of piezoelectric transducers in combination with electrical components, called passive vibration control shunt circuits and flexible piezo patches [33]. A study was made via experimentally and numerically for vibration control with a wide range of operating temperatures [34]. The core principle consists of the transformation of the host structure's vibrant strain energy into electric energy. By using the direct piezoelectric effect, routing this energy through the shunt circuit where it can be partly absorbed was achieved. These are subsequently a superior class of energy conversion materials with associated mechanical and electrical features; shunt circuits coupled with such materials play an important role in the performance of wave propagation and/or vibration control in smart periodic structures [35].

With low and medium ranges of frequency, information can be collected for a damped thin plate with piezoelectric patches that are associated with the time-varying RL shunt circuits. The plate damping was considered in the lower range and five time-varying shunted patches were used [36]. As a result, the damping factor and frequency were executed via PZT effects in such a way as to either switch between given values, or sweep within certain ranges, to control the resonant response of targeted flexural modes of the plate. Figure 2 shows a smart panel made of a thin rectangular plate of aluminum and a series of five thin piezoelectric patches polarized in the transverse direction [36]. The physical and geometrical parameters of the plate and piezoelectric patches are summarized in [36]. The panel's dimensions and physical properties were selected to represent a part of an aircraft skin wall made up of two stringers and two rings, which can be easily modeled as a supported panel. The patches were chosen so that they would occupy a good part of the panel and have the same width as the panel. As a result, four patches were bonded on one side of the panel and the fifth patch was bonded on the opposite side at the panel's middle, as seen in Figure 2b. The patches are made of a traditional piezoceramic material that is isotropic in the x–y plane and therefore can effectively act on the two-dimensional hosting plate structure. The plate is subjected to a white noise rain-on-the-roof excitation, which is an idealized excitation made up of a uniform distribution of uncorrelated point forces that similarly excites the structure's natural modes. The rain-on-the-roof excitation has been approximated in this analysis with a 4-4 finite array of forces such that they are divided around a flexural wavelength at 1400 Hz and hence achieve the even modal excitation in the entire frequency band considered in the simulations, as seen in Figure 2a.

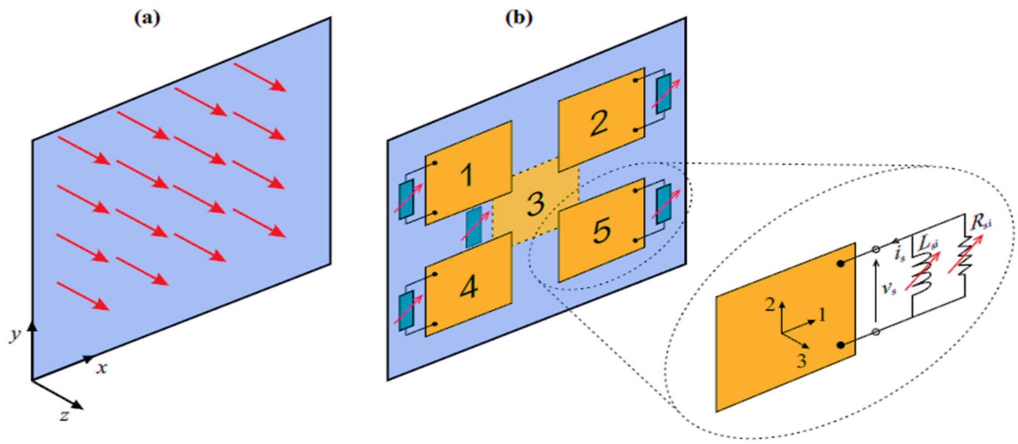

Figure 2. Vibration plate with shunted piezoelectric patches. Reprinted from [36], Copyright 2021, with permission from Elsevier.

With a parametric actuator and control theory in a distributed form, the active vibration damper of a cantilever beam was designed. A piezoelectric polymer, polyvinylidene fluoride (PVDF), was the distributed-parameter actuator and Lyapunov's second approach was used for distributed-parameter systems to design a damper control algorithm [37]. Honghao [38] has also conducted an experimental study of the AVC of a piezoelectric laminated paraboloidal shell by positive position feedback. The piezoelectric active damper was proposed by Bailey et al. [37] in 1985. The first modal damping ratio of the beam was increased to 4.5 times with distributed PVDF piezoelectric film layers laminated on one side of the flexible cantilever, and these PVDF patches were laminated inside and outside the shell, of which eight were used as sensors and eight as actuators to monitor the vibration of the first two natural modes. Through the frequency response feature review, Modal VIEW software [38] obtained lower natural frequencies and vibration modes of the paraboloidal shell. Hagood and Flotow [39] derived the mechanical impedance for the piezoelectric part shunted by an arbitrary circuit. It was found that the shunted piezoelectric has a frequency-dependent stiffness and loss factor that also depends on the shunting circuit.

An electrical resonance is introduced by shunting with a resistor and inductor, which can be optimally tuned to structural resonances in a way similar to a mechanical vibration absorber [39]. In the moving system, it is caught in its high stiffness state to store energy in actuators. The motion of the device is responsible for obtaining control back from the actuator, so the actuator is changed to a low state of stiffness, dispersing the energy [40].

It is necessary to know that the actuators for the structural portion of wing vibration used in aerospace applications are controlled by the actuator. In this case, highly flexible multi-functional wings with embedded piezoelectric material are used for adaptive vibration control and energy harvesting, according to recent studies by Natsuki [41]. The use of an actuator for an unmanned aerial vehicle, combined with a non-destructive health monitoring system based on vibration, was proposed. The indication was that someplace excitation and record acquisition occur simultaneously from the piezoelectric transducer against a truth expansion. This removes the need for roofing training with hundreds of monitoring sensors, as this concept uses a particular piezoelectric transducer to monitor a structure. By converging unmanned aerial vehicles, the expected handiwork creates new fields of inquiry [42]. A Simple-FSDT-based iso-geometric approach with the mathematical expression for piezoelectric functionally graded plates has been studied on vibration analysis [43]. Such studies have been found to shape the control of the antenna reflector to the desired shape—a closed-loop iteration based on the influence coefficient matrix and FE model [44]. The AVC method was also found in civil infrastructures in which the review has been made by considering different types of application of civil structures that have been controlling piezoelectric material [45]. For the case of suspension bridges, an investigation has been made for the active damping controlled by decentralized integral force feedback [46] and, similarly, model frame structures, [47] including smart model frames [48] and loop share buildings [49], are also controlled.

3.2. Noise Control

Controlling noise can be done through the smart piezoelectric transducer in any type of structural device. This section illustrates the previous work done by the researchers to control the noise using piezoelectric materials.

Aridogan and Basdogan [50] analyzed existing advanced systems of active vibration and noise control for plate structures with varying boundary conditions. Numerical and experimental techniques were reviewed to search various facets of control structural design. First, according to their designs, they identified the controls, then compared their vibration and noise reduction efficiency, and at last included recommendations for further development. Shivashankar and Gopalakrishnan [51] reviewed the use of piezoelectric materials for active vibration, flow control, and noise to seek analysis to outline the improvements achieved in both areas by focusing solely on the application of the piezoelectric material. Gripp and Rade [52] offered a comprehensive literature analysis of numerous piezoelectric shunt damping techniques industrialized for vibration and noise reduction in mechanical systems, an evaluation of the fundamental principles, as well as design procedures and computational simulation of piezoelectric shunt damping variance. Casadei et al. [53] described simulation and experimental examinations of the operation of a periodic series of piezoelectric forced RL patches for the reduction of broadband noise radiated in an enclosed cavity by a flexible layer. Frequency bandgaps described the reaction of the resultant periodic system where vibrations and related noise were highly attenuated.

Ang et al. [54] provided an analysis of current practices in various industries, such as automobile, maritime, aerospace, and defense used for cabin noise control. Nevertheless, the focus was put on cars and armored vehicles. In general, car cabins typically consist of thin structural plates, where the simple frequency usually drops below 200 Hz. Booming noise happens if a certain structural mode couples with a particular acoustic mode of the cabin. Lai et al. [55] investigated the effects of equivalent series resistance on the noise mitigation performance of piezoelectric shunt damping, developed an understanding of the impact on noise mitigation efficiency of the equivalent series resistance (ESR) of the piezoelectric damper in a piezoelectric shunt damping (PSD) device and showed that an improved ESR contributes to a substantial improvement in noise transmissibility due to a decrease in the mechanical damping of the device.

Salvador et al. [56] presented the possibility to extort such noise in the form of electricity into renewable energy using a combination of a piezoelectric transducer and a super-capacitor. A prototype was strategically built and constructed between the streets of Lerma and Nicanor Reyes usually congested by traffic, situated within the university belt area in Sampaloc, metro manila, Philippines. Araujo and Madeira [57] obtained an active control bonded with PZT sensors and actuators to optimal noise reduction solutions in laminated viscoelastic soft-core sandwich plates. An in-house finite element implementation of the active laminated sandwich plate was used to accomplish the frequency reaction of the sheets. Using the Rayleigh integral method, the sound propagation features of the panels were determined by computing their radiated sound power, since the structural/acoustic problem are loosely coupled. As an actuator and sensor based on a numerical solution method also called the generalized differential quadrature approach, intelligent control, and dynamic investigation of a reinforced composite graphene nanoplatelet (GPLRC) cylindrical shell surrounded by a piezoelectric layer were provided (GDQM). The strains and stresses were measured using the First-order Shear Deformable Theory (FSDT). The results showed that the PD controller's weight fraction, viscoelastic base, slenderness factor, external voltage, and graphene nanoplatelets (GPLs) have a major impact on the vibration and amplitude of the GPLRC cylindrical shell [58].

Li et al. [59] discussed several simple instruments and techniques widely used in various controlled objects for different components of the active control system. For reducing periodic noise produced in a high magnetic field, such as noise generated by magnetic resonance (MR) imaging devices (MR noise), an active noise control (ANC) method was suggested. Optical microphones and piezoelectric loudspeakers were used for the proposed ANC system, as specialized acoustic equipment was required to address the high-field issue and consisting of a structure mounted on the head to control noise near the user's ear and to recompense piezoelectric loudspeaker's low performance [60].

3.3. Active Control

The damaged structures, such as cracked and delaminated composite, which are damaged due to the external load or accident can also be controlled by the piezoelectric material application. In many cases, composite material is inexpensive and lightweight, but due to high rigidity, it can crack or delaminate easily as compared to other types of body kit materials [61], and such type of delamination can be controlled by a PZT actuator. As an active control, PZT actuators were used over the last two decades, during which researchers have investigated various subjects, such as the control of buckling, stresses, and cracks in the structures [62], and the use of the piezoelectric actuator to sense and operate the structure has been a point of interest [63–69].

The PZT actuators have adequate output in compromised systems. The active electromechanical coupling effect greatly alters the properties of the damaged structure due to its adjustable mechanical properties [70] for active control in damaged structures in which Rao et al. [71] investigated an aluminum plate with a central crack for repairing, by using four equal sizes (40×40 mm^2) patches made up of piezoelectric material polarized in the X-direction. The active repair of an aluminum center-cracked plate was carried out to minimize the stress concentration at the crack tip by bonding four piezoelectric patches to the host structure. The single-strap adhesive joint system has been analytically modeled to research the effect of piezoelectric patch surface bonding and stress distribution in the adhesive layer [72]. Investigation of the delamination control of composite plate with the PZT actuator by inducing low-speed impact using explicit FE code LS-DYNA was also carried out [73] in such studies.

Sohn et al. [74] developed a signal processing technique for composite plates, to predict delamination. This method, together with an active signal system, was used for the continuous monitoring of the composite structures under consideration. The parameters that influenced the delamination size detection were the distance between piezoelectric patches, actuating frequency, wavelength, and the size of the grids. They proposed a damage detection algorithm that easily detected the delamination under different boundary conditions and temperatures [4], to repair delamination to prevent beam fractures. Their findings showed that the voltage needed in beams to repair delamination depends solely on the delamination position. A related study was conducted using ANSYS software by Liu to restore delamination using piezoelectric materials. It has been indicated that the lower voltage is ideal and economical for safer operations, while the patch length, layer and thickness are highly influential [75].

The use of piezoelectric patches for repairing the delaminated beam under static loading conditions was also reported in [76]. The higher voltage suggested for a spring model to analyze the bonding adhesive effect on the output of piezoelectric patches (single and multi-layered patches as shown in Figure 3) used as active cantilever beam repair [6,76]. To decrease the stress intensity factor, the voltage applied to close the crack was higher [77,78]. Another study was documented by Wu and Wang using FE analysis during static loading conditions. To eliminate compressive and tensile forces around the delamination site, they concocted a discrete electrode from piezoelectric actuator patches to reduce stress singularity around the damaged part [79–84].

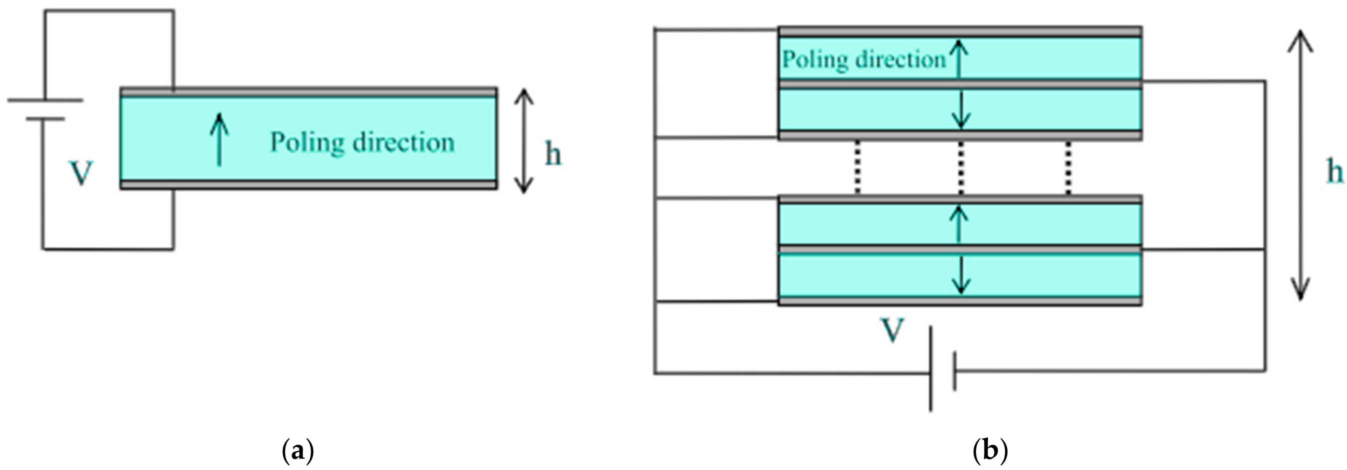

Figure 3. Piezoelectric patches: (**a**) single-layer patch and (**b**) multi-layer patch. Reprinted from [6], Copyright 2021, with permission from Elsevier.

Furthermore, an example of this type of study has been found by Wang [85], in which the model with a simply supported beam undergoing axial compression was tested. At the center of each actuator's surface, a resistive strain gauge is connected. Each piezoelectric patch is polarized along the Z-axis as an actuator and applied through its thickness with a voltage. A cantilevered beam exposed to axial compression was the second design. The actuator pair positions were set to shift from the clamped end to the free end along the beam to find the optimum locations.

In recent investigations, Abuzaid et al. [86–91] utilized the piezoelectric actuator (PIC 151) to control the crack propagation in aluminum rectangular thin plates and they determined the fracture parameters, such as stress intensity and stress concentration factors. The ideas developed to produce stress (compression/tension) on the stress distribution around the hole and along with the width of the damaged plate by the piezoelectric actuator. The methodologies were adopted via experimental work for an edge-cracked plate [92] and edge- and center-cracked analytical modeling using the crack-closer method [91] and weight function method [92] and numerical simulation via ANSYS simulation [92,93]. To determine SIF for the center-cracked plate, concentrated on the location of the piezoelectric patch on a cracked plate with respect to the dimension by changing the patch location and thickness of adhesive layers. For the same reason, piezoelectric actuators additionally attached a composite patch for the repair of the cracked plate with the determination of SIF [94] and SCF [95].

4. Structural Health Monitoring

Generally, SHM used in wide applications with its advanced technologies and a number of research studies has been reported in the literature over the last two decades. For the sake of piezoelectric material application, this review has reported with some fundamentals/methodologies/overview used to perform SHM on a damaged structure and its enhancement. The enhancement of orthotropic and isotropic material for piezoelectric transducers can improve its properties significantly. The structural strength and stiffness of the material together make it a high-performance material. Delamination in composite structures plays a key role in reducing structural strength and rigidity, subsequently reducing device integrity and reliability so that the lamb-wave technique can be efficiently produced using piezoelectric transducers embedded within a composite plate for health monitoring [96]. The SHM is an innovative technique built from non-destructive testing (NDT), blends sophisticated sensor technologies with intellectual algorithms to cross-examine systemic health conditions [63]. Statistical model creation is concerned with the implementation of algorithms that use the extracted features to measure the extent of the damaged structure. These algorithms can be classified into two classes, as shown in Figure 4. To improve the damage detection process, all of these algorithms test statistical distributions of the measured or derived features. A broader and more comprehensive discussion can be found in [97,98], which are two fundamental texts for all people working on SHM. Moreover, supervised learning strategy for classification and regression tasks applied to aeronautical SHM problems was discussed in detail by Miorelli et al. [99].

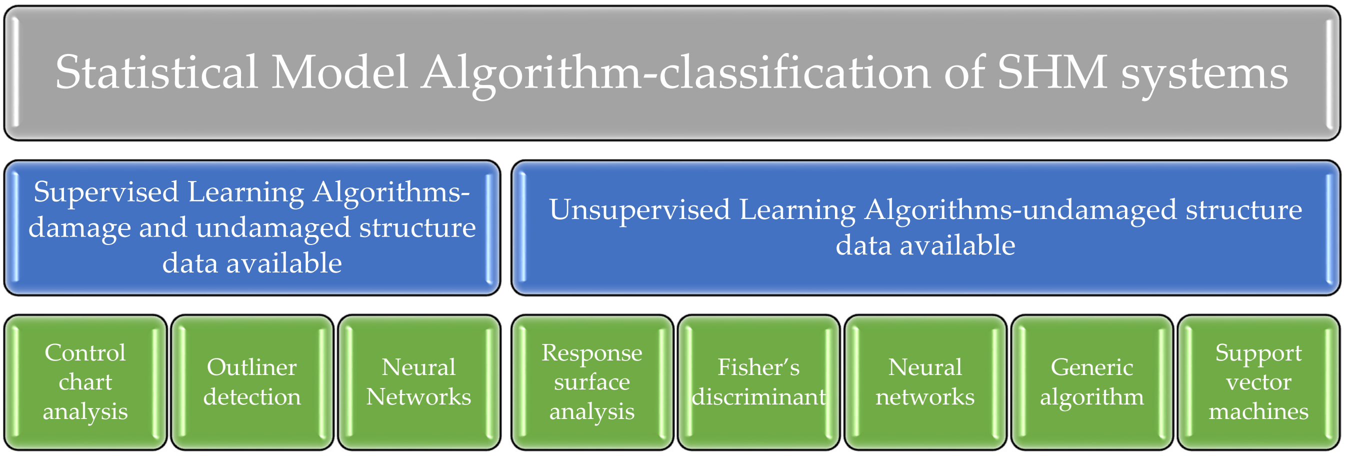

Figure 4. Algorithms classification for Statistical Model Development for SHM.

4.1. *Aerospace Structures*

For the identification of minor emerging vulnerabilities in engineering systems, several researchers are focusing on SHM techniques based on guided wave propagation. Low-velocity impacts on structures may cause these defects, which are often not apparent to the naked eye [100,101]. Instead of using traditional non-destructive methods, guided wave propagation techniques for SHM are often used in the aerospace industry [102]. Continuous SHM for aerospace systems during service is a difficult but promising technique [103]. As a result, several researchers are developing these techniques for the continuous SHM of aerospace systems when they are in use [30,104,105]. Because of the environmental consequences, sophisticated SHM methods are very difficult to adopt even in ideal circumstances [106].

Because of its ability to detect very small losses, guided waves are the most active area of study in SHM for aerospace, as demanded by the aircraft industry. The definition is straightforward, as seen in Figure 5: A PZT bonded/embedded into the structure emits a short ultrasonic pulse (the frequency used is a few hundred kHz) that propagates as an elastic wave through the plate and is absorbed by other PZTs, though warped. The signals received are saved and compared to signals received later in the structure's lifespan. Any new signal distortion must be the result of a structural change in the emitter–receiver PZT direction. In flat laminates, the idea works well, and minor delamination's produced by an effect can be observed and even found. The method also fits well for cylindrical tubing [107]. As the concept is applied to specific systems with boundaries, stiffeners, and thickness adjustments, the complexities increase. Elastic waves behave like all other waves, with reflection and refraction happening at either interface, complicating the signals obtained [108]. Furthermore, variations in thickness encourage mode switching, and all modes are dispersive, moving at varying speeds. As a result, signal processing and measurement were much more challenging. The obtained signals are often distorted by temperature and operating loads [109]. Modeling wave propagation and association with defects with structures with increasing geometrical complexity, such as stiffened structures, is currently a major focus [110].

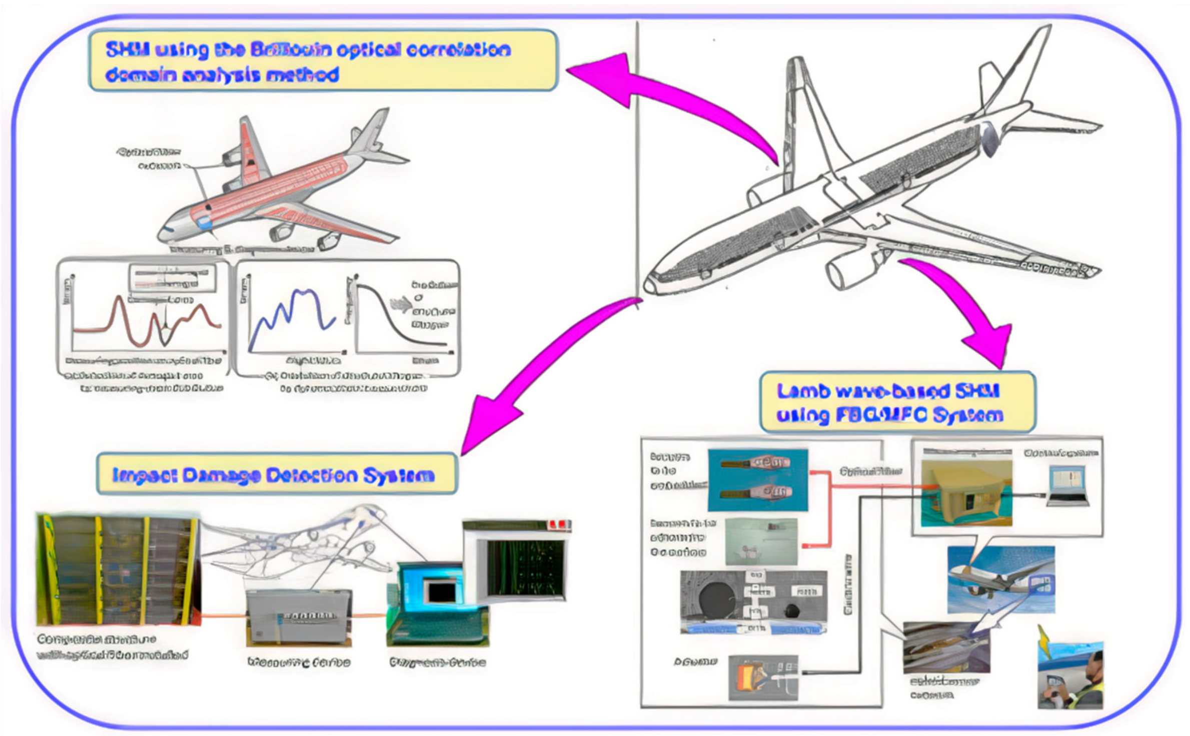

Figure 5. Damage detection alternatives with fiber optic sensors [99]. Reprinted under the Creative Commons (CC) License (CC BY 4.0).

While extensive SHM advancement has been accomplished, a great deal of work is still needed for more practical applications of SHM in composite materials [111]. Through a down-select procedure based on the control and health monitoring of structural design for the space vehicle, the tested SHM sensors and their sensing techniques were chosen [112]. To design online SHM systems for aerospace vehicles or aircraft, an extended fluid–structure interaction was proposed. It is a strongly coupled version of a standard FSI problem with a wave propagation problem coupled, in which the wave propagation problem is posed on the moving mesh which is automatically adopted from the FSI problem at each time stage [112].

For the damage/delamination studies, to identify skin/stiffener debonding and delamination cracks suitable for laminated composite structures, the SHM method was proposed [7]. An improvement of the SHM methods, the lamb-wave techniques for quasi-isotropic graphite/epoxy thin patches and sandwich beams containing representative damage modes, transverse ply cracks, delamination, and through-holes were studied. The detection of damage by measuring transmitted waves with piezoceramic sensors was experimentally optimized and given a technique capable of simple and precise determination [113], and it is recognized that piezoelectric materials constitute both the electrical and mechanical properties and are used in the field of SHM engineering [114]. Moreover, piezo composite [115] patches were applied to detect the defects using lamb-wave focusing [116]. At the time of design, the piezoelectric sensor was embedded and demonstrated in the structure and the bonded patch served as sensors for both the global dynamic technique and the EMI technique [117]. Assessments of SHM for fatigue cracks in metallic structures were made by using lamb waves guided by piezoelectric transducers [118]. The piezo ceramic transducer-based electromechanical impedance technique (EMI) and the digital image correlation (DIC) method that uses structural surface adjustments with monitoring were experientially studied [119]. The consignment of tiredness generally exacerbated the fissure if there were any defects in the structure. The adjacent active electrode multiple-crack monitors triggered numerous airplane defects that were caused by EMI output and the DIC system in the specimens over the weakness test [119]. Although the EMI analysis is complicated, it can be carried out by breaking down the structural loss into actual and theoretical impedance components. Figure 6 depicts the ultimate process for SHM depending on impedance.

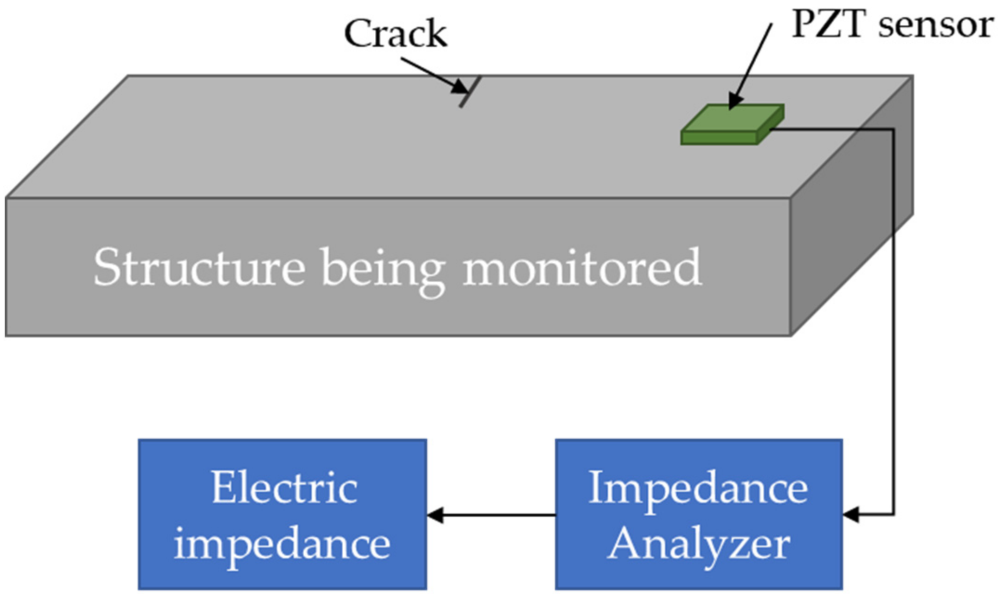

Figure 6. SHM of the cracked structure by impedance analyzer.

Sensor amplifiers and data acquisition units make up passive diagnostic hardware. Through a sensor network, the impact monitoring system collects stress wave signals produced by impact loads [120]. Figure 7 illustrates the process of the impact monitoring of aircraft structures.

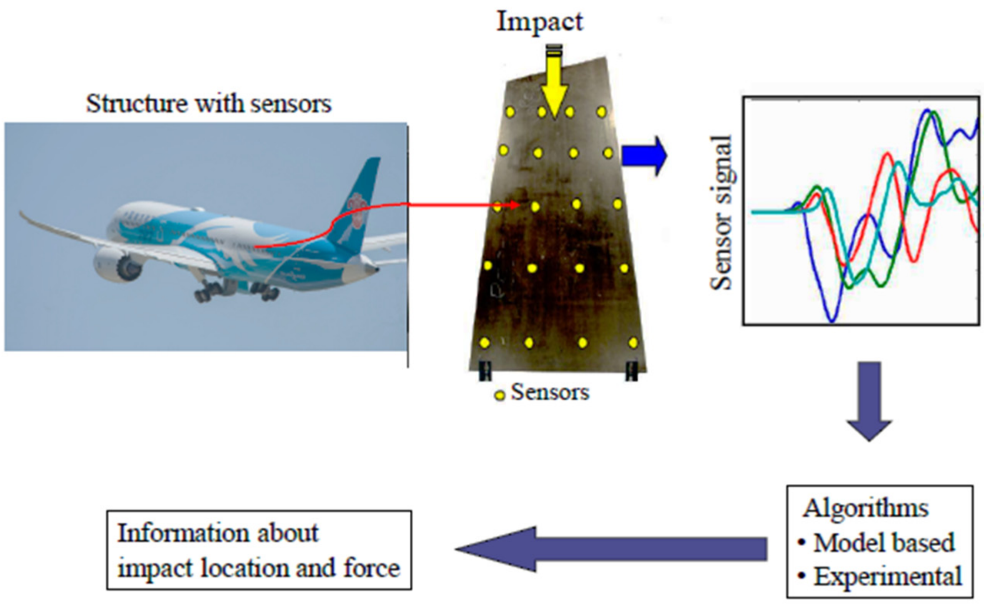

Figure 7. Impact monitoring of aircraft structures [120]. Reprinted under the Creative Commons (CC) License (CC BY 4.0).

Richard et al. [121] examined, by the analytical method, the vibrations of the piezoelectric composite plate through cylindrical bending and experimentally established the various vibrations for the bolted composite plate based on the SHM technique. This novel SHM approach combines vibration-based thermography with the idea of local defect resonance to create a novel SHM method. The use of hard shakers to apply high excitation and infrared cameras to observe thermal responses are also major challenges for face layer debonding detection in aerospace sandwich structures [122]. For an aircraft skin health monitoring system, a piezoelectric sensor network with shared signal transmission wires was proposed with multiple PZT using the design principle method [123]. On such cases, the PZT sensor network, which uses mutual signal communication cables, must be wired longitudinally and transversely, which is difficult for some real-world aircraft structures with several frames and ribs. Some suggestions has been made and reviewed based on the piezoelectric sensors for aerospace structures for SHM [124].

As an overview of this section based on the above studies using the SHM approach, some conclusions can be derived. For the case of composite materials, this method was found to be very useful to detect delamination, cracks, and minor damages. With the SHM technique, it is possible to improve the mechanical and electrical properties of intact and damaged materials. Hence, using piezoelectric transduces for SHM techniques will be an innovative concept in engineering research fields such as aerospace structures. The example is shown in Figure 8. By improving the material's properties, and particularly the material's toughness, the slope of the curve is decreased and the durability of the structure is increased [125].

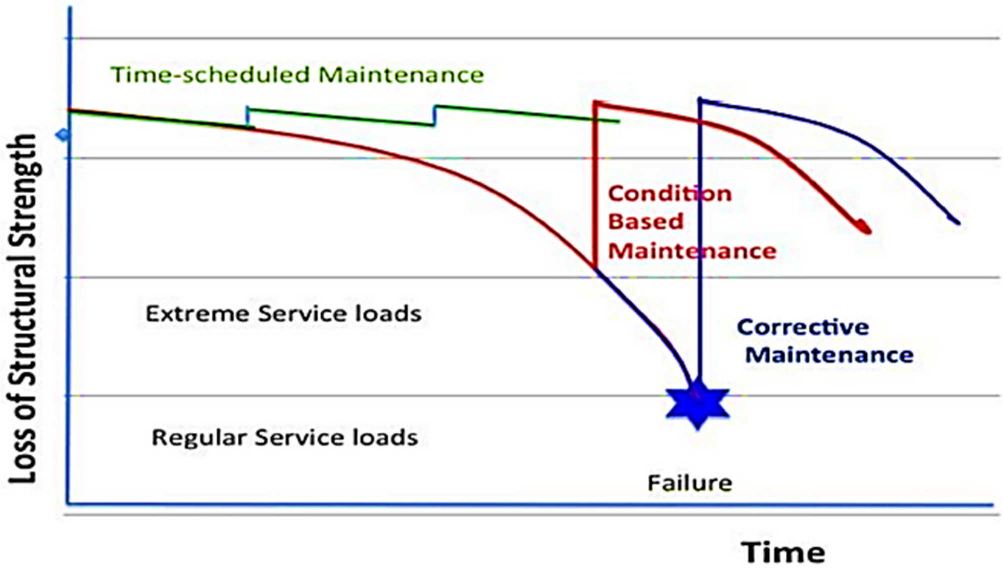

Figure 8. Maintenance strategies with/without SHM [125]. Reprinted under the Creative Commons (CC) License (CC BY 4.0).

In critical view, a piezoelectric wafer active sensor has been used to monitor the onset and progress of structural damage, such as fatigue cracks and corrosion, on current ageing aircraft structures. The state of the art in active SHM sensors and detection of damage was reviewed by the researchers [126]. In general, the efficiency of the piezoelectric sensor is the most versatile and low-cost sensor. For global and local-level damage and cracks, piezoelectric patches have been used as a sensor and they explored the possibility of an embedded piezoelectric sensor. As multi-purpose sensors for research, piezoelectric patches were also used, using various methods such as modal analysis, acoustic emission, lamb-wave, and strain-based methods simultaneously by adjusting driving frequencies and sampling rates [127]. There are relatively fewer sensors in the piezoelectric material and are therefore suitable for engineering applications such as aerospace, automotive, and civil structural health monitoring [128].

4.2. Concrete Structures

Due to the advancement of piezoelectric material, it has been used for civil concrete structures to detect and repair damages. Hence, this section reviewed the works related to civil engineering structures.

SHM field monitoring, which uses embedded sensors or real field testing to track the condition of existing or new civil engineering infrastructure, is an emerging technology. The use of SHM as a critical component of infrastructure design will be critical in the construction of the next generation of smart civil engineering structures. Intelligent sensing systems have four key components: (i) sensors and actuators that collect information and operate in a target environment; (ii) a network infrastructure for data and control signal transmission; (iii) data processing and visualization systems; and (iv) basic analysis and decision-making applications.

The presented model deals with the bonding layer as a mass-spring damping mechanism between the piezoelectric patch and the substrate structure in the corresponding electromechanical analysis. The effect of the bonding layer was therefore considered on the dynamic interaction between the piezoelectric sensor drive and the main structure [129]. The piezoceramic transducer was developed in the contemporary past as an anti-intelligent material commonly used in electromechanical impedance (EMI) and guided ultrasonic wave broadcast techniques. A piezoelectric transducer interrelates with the horde construction in the EMI technique to study exclusive health marks as an inverse action of structural impedance in the incidence of the sensitive region on the application of the high-frequency structural load [30].

Effective monitoring of rock components in civilian infrastructures such as tunnels and caves remains challenging. Yang et al. [130] introduced the use of smart fiber-optic and PZT impedance sensors for integrated rock condition monitoring, load profile monitoring/detection, and damage assessment. Rock samples were loaded periodically, and their condition was constantly monitored by fiber-optic and piezoelectric sensors. The surface of a fiber optic sensor was based on a multi-fiber Bragg grating sensor in combination with rock samples. The strain sensitivity was compared to that of a conventional electrical strain gauge. The EMI technique of the piezoelectric transducer, consisting of real and virtual parts, served as an indicator for predicting the state/integrity of the host structure. In practice, however, components such as panels, beams, and columns were constantly subjected to external loads. Experimental and statistical studies showing the impact of exposure to valid electronic results were studied [131]. Moreover, it was noted that an acceptance indicator was better than a conductivity indicator for locating pressure in situ in the main structure. This observation was further confirmed by statistical analysis.

Experiments were performed to examine the complex tribulations in the EMI technique's real-life implementations, seeking to moderate the space between suspicion and application. Experimental studies showed that the bonding thickness is expected to be much thinner than one-third of the scrap to duck any negative realization induced by the reminiscence of the piezoelectric direction on the permission signatures restoring the structural actions of the horde. In order to be thoroughly connected to the thickness of bonding, the hotness on the access signatures was created, as an intensification of hotness would ease the tautness of the bonding sheet, resulting in disturbing strain transfer [132]. The structural mechanical impedance extracted from the incoming piezoelectric electromagnetic signal is used as an error indicator. A comparative study of the sensitivity of the transmission of electromagnetic waves to damage concrete structures and the mechanical resistance of the structure was carried out. The results show that structural mechanical impedance is more susceptible to damage than EM, which is a better indicator of damage detection. Genetic algorithms were used in dynamic systems to find optimal values for unknown parameters. The experiments were carried out on a two-story concrete frame, subject to basic vibrations that simulate an earthquake. Several piezoelectric sensors were regularly assembled and connected to the frame structure to obtain the PZT-EM approval method. The relationship between noise and the disturbance distance of a PZT sensor was examined to cover the sensitivity and sensitive areas of the PZT sensor [133].

Xio and Jiang [134] proposed a method for detecting shear bolt failure in reinforced concrete composite beams based on EMI measurements of PZT ceramic sensors. Several piezoelectric patches were superficially attached to the top flange of a steel beam and concrete slab, and their EMI was measured with an impedance analyzer before and after loosening the connecting screws. Based on the impedance measurement, the impedance spectrum was estimated and compared for the presence of interconnecting volts using several general error statistics including standard deviation, absolute percent deviation, and correlation coefficient deviation. Five kinds of scratch requirements were considered to examine the impedance ethics at sundry frequency bands. Reliable regulations are originating by control and analysis. Equally, the core median pays off deviation and the correlation coefficient deviation smash up indices are adapted for detecting the structural damage. The mathematical and experimental studies verify that the EI structure can accurately detect changes in the quantity of break-in armored definite slabs. The smash up alphabetical listing changes evenly with the vastness of costs to the sensor [135]. Piezoelectric transducers in the structure of smart aggregates are embedded into the specimen during casting. Piezoceramic equipment can be as old as actuators to breed peak frequency vibrating waves, which promulgate in physical structures; meanwhile, they tin beside old sensors to reveal the waves [136].

Load-induced structural stress/compression stress and stress-induced injury were tested qualitatively by evaluating and contrasting the electromechanical input technique typescript with that of the non-stressed piezoelectric transducer. Quantification assessment of stress and harm through algebraic source shabby pay deviation indicator was also presented [137]. For damage detection of a 6.1 m extensive non-breakable physical attachment bent cap, piezoceramic transducers are used. At pre-determined spatial locations before casting, piezoceramic transducers are embedded in some designs. This delves into being able to be cautious as a prior work persistence, wherever four piezo ceramic transducers were embedded near one point of the bent cap in planar locations. This involves ten piezo ceramic patches in four separate cross-sections embedded at spatial locations for the investigation [138].

Talakokula et al. [139] studied the effects from a series of accelerated oxidation tests performed on rebars embedded in separate cubes in which measurements were ready to float up bonded on rebars using the electromechanical impedance technique via piezo ceramic patches. The comparable structural parameters derived from the entry signatures of the PZT information were measured against the deterioration objective based on which a new representation of the oxidation assessment was proposed. The experimental fallout suggested that in the practical detection and quantification of the decomposition, equal parameters were efficient. To continue its trend, realistic studies associated with the EMI method for the past decade have been reviewed. New ideas and dreams planned by a variety of writers were also discussed, and the tabloid ended with a discussion of the promising guidelines for imminent works [140]. In the next study, the PZT sensor was placed near the crack on the concrete sample surface, from which the impedance and admission were decided by a connected impedance analyzer to determine the structural conditions [141]. The wireless smart aggregate SHM device configuration and signal flow are depicted in Figure 9. A detected reinforced concrete (RC) structure, a signal excitation module, a signal data acquisition module, a wireless communication module, and a power module make up the established device. The smart aggregates are pre-embedded in the RC structure that was observed, and the detailed study can be found in [142].

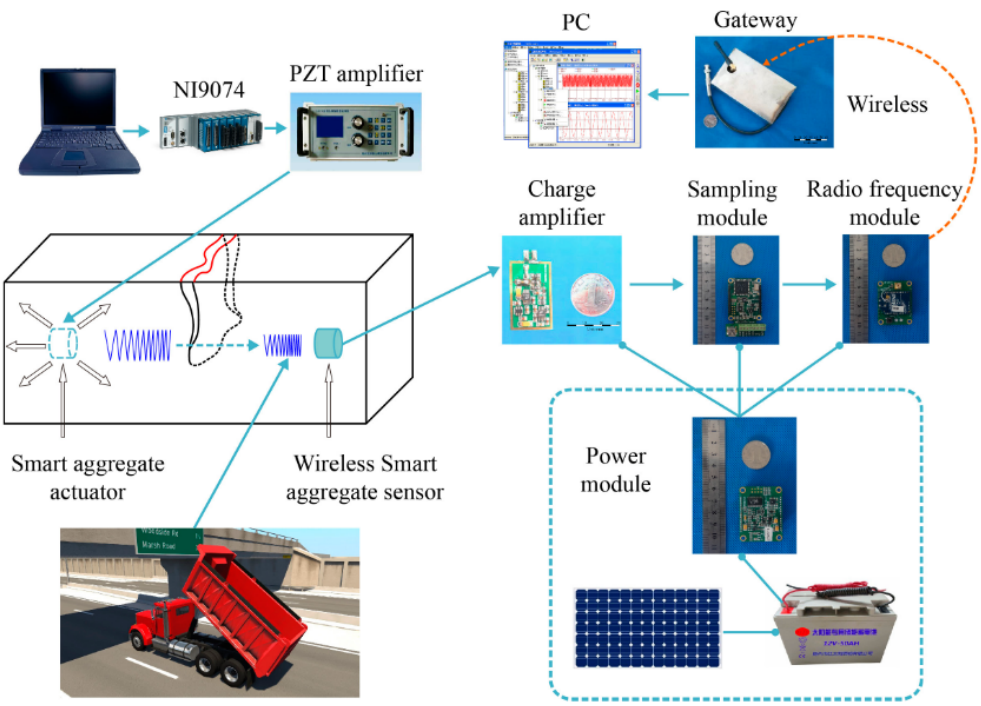

Figure 9. System setup and signal flow of the SHM system [142]. Reprinted under the Creative Commons (CC) License (CC BY 4.0).

4.3. Practical Issues

Numerous experiments have been conducted in this field since the advent of the EMI methodology, with many reporting positive findings. However, the majority of the experiments were conducted in laboratories or were mostly theoretical, raising concerns about their potential in real-world applications, especially in harsh environments [140]. While damage to the structure alters the impedance signature, other variables such as temperature and the reliability of PZT transducers may also alter the signature. Sun et al. [143] used the EMI technique in a temperature-varying environment and found that raising the temperature softened the total stiffness of the host system, shifting the resonance frequency spectrum and changing the peak amplitudes. By horizontally rotating the signature, the authors used cross-correlation to eliminate signature variance due to temperature change. Park et al. [144] observed that the actual part of impedance signatures could be preferable to the imaginary part since the real part of the free PZT patch's signature shifted just slightly with temperature fluctuations. Besides, the authors proposed another technique for compensating for signature variations caused by temperature changes; several other researchers have also looked into this subject.

Grisso and Inman [145] suggested using a frame structure to perform experiments under different temperatures to separate the temperature variance effect from sensor defects. The researchers discovered that the estimated susceptance slope had a linear relationship with temperature changes. Wandowski et al. [146] evaluated the suggested temperature correction algorithm using carbon-fiber-reinforced polymer samples. The two-step algorithm works by shifting the signature first in the horizontal direction using cross-correlation, then in the vertical direction using signal normalization with root mean square values. Although many techniques for compensating for the temperature effect of the EMI technique have been proposed, completely compensating for this effect is extremely difficult. Some peaks can change or increase/decrease in amplitude more than others, making impedance signature variations unpredictable [147].

5. Challenges and Opportunities

The critical analysis and discussion of the previous selected studies of this review have been categorized into SHM and control of structures. However, over the last two decades, there have been several studies reported based on the use of piezoelectric materials in engineering structures, and the challenges and opportunities of the review have been illustrated from recent studies.

In order to tackle real-life field implementations, a lot of work is being put into studying these deployment problems in SHM techniques. For more than two decades, the EMI technique has been used, and based on recent studies, numerous problems must be resolved before it is practical to structures. The technique, which likely played a part in the formation of a large amount of force in SHM systems, involves the wear and tear of a unique piezoelectric for sensing and exciting the mass structure. The study presents a modified model of the EMI of piezoelectric drives from many researchers. The presented model deals with the bonding layer between the piezoelectric patch and the familiar structure as a mass-spring damping system in the corresponding electromechanical analysis. In the contemporary past, the piezoceramic transducer has emerged as a useful smart material, which is generally employed in EMI and guided ultrasonic wave broadcast techniques. In the EMI technique, a piezoelectric transducer interrelates with the horde construction for findings in exclusive health signature, as an inverse behavior of structural impedance and at what time it is exposed to high-frequency structural excitations in the occurrence of the sensitive field. Effective tracking of rock components in civilian infrastructures such as caves and tunnels remains challenging.

SHM-based electromechanical impedance damage detection is rapidly evolving in structural design. In the electromagnetic impedance method, a piezoceramic transducer is mounted on the surface of the main structure to operate electrically. The EM technique of the piezoelectric transducer consists of real and virtual parts, serving as an indicator for predicting the state/integrity of the host structure. In practice, however, components such as panels, beams, and columns are constantly subjected to external loads. The EM approval mark obtained for permanently loaded structures is different from that acquired in the event of structural damage. In a new era in the subject of SHM focused on non-destructive assessment, the beginning of smart tools such as the piezo-impedance transducer and optical fiber has begun. Thus, the research on the EMI potential using a piezo-impedance transducer is often laboratory based and largely theoretical. The technique's real-life attention, especially in harsh environments, has typically been challenged. The repeatability of electrical input signatures obtained from the floating piezoelectric patches bonded to aluminum structures was initiated to be brilliant for up to one and a half years. The EMI based on piezoelectric ceramics for SHM has been successfully applied in a variety of technical systems. However, a basic study of the sensitivity of piezoelectric impedance sensors to fault detection is still needed. Traditional EMI methodology uses the EM tolerance of the piezoelectric (as opposed to impedance) as a failure indicator, making it difficult to determine the impact of damage on structural properties. The following are some open research areas for SHM for engineering structures and applications that may need focus.

- It is difficult to install the piezoelectric to the host structures and generate a high-frequency range; therefore, the piezoelectric is packaged in a way that makes installation easier [148].
- Modern civil infrastructure projects were designed to provide specialized functionality for multi-purpose applications in extreme weather situations, including earthquakes, hurricanes, and typhoons. These dynamic structural structures raise significant questions about their stability. Integrating a network of smart and embeddable sensors into civil infrastructure systems with local artificial intelligence (AI)/machine learning (ML) data-processing platforms is a promising solution to this problem, allowing next-generation smart, civil infrastructure systems to be installed on the skeleton of conventional systems [149].
- The lack of a computational platform on which to develop new techniques for realizing massively distributed smart sensors is one of the crucial issues listed in [150] and the possible development of the next generation of SHM systems.
- Although they have been the focus of intense study for many decades, computational approximation and simulation of fluid–structure interactions remain an undeniably difficult topic with many unsolved problems and concerns, and the "arbitrary Lagrangian-Eulerian" method is a standard framework for solving fluid–structure interaction problems, as we emphasize [112].
- SHM can be used to measure civil industries that are live loads on bridge systems as well as environmental loads and to spot any significant differences from the values assumed in bridge-building codes. Given raising questions about climate change and its possible effect on the stability and serviceability of concrete bridge systems due to increased wind loads, floods, thermal gradients, freeze–thaw cycles, deicing salt use, and other factors, this is becoming an important topic [151].

Strong suit monitoring is critical in the first part of the age of structures to determine the skill of the structures for operation. Strong point monitoring techniques based on piezoelectric avails an innovative experimental approach including performing material health monitoring at primitive ages. The piezoceramic transducer has emerged as a new tool for the health monitoring of large-scale structures expected to benefit from their low cost, work sensing, clever response, simplicity for implementation, and availability, not the same shapes and simplicity. As far as piezoelectric materials are concerned, Figure 10 provides the figures and the timeline for different fields of use. Figure 10 concentrates on the use of materials and the hope is that this number will keep growing in the near future within engineering structures. This expectation is due to fact that these materials have already built a reputation, and because of their advancement and growth, which were previously stumbling blocks for conventional approaches, they have encouraged new possibilities in resolving various engineering issues. The existing literature provides a clear picture of the progressive production of piezoelectric actuators in these fields in the areas of SHM. The study of effective repair, on the other hand, is still in its infancy. One important thing to be noted is that piezoelectric-based MFC actuators can be preferred over ceramic-based materials due to their high impact resistance and flexibility. The development of piezoelectric materials creates new possibilities for the repair and control of active damage techniques. Active control is a very challenging task, in both technological and design aspects. The implementation of research software to explain the repair process would be important.

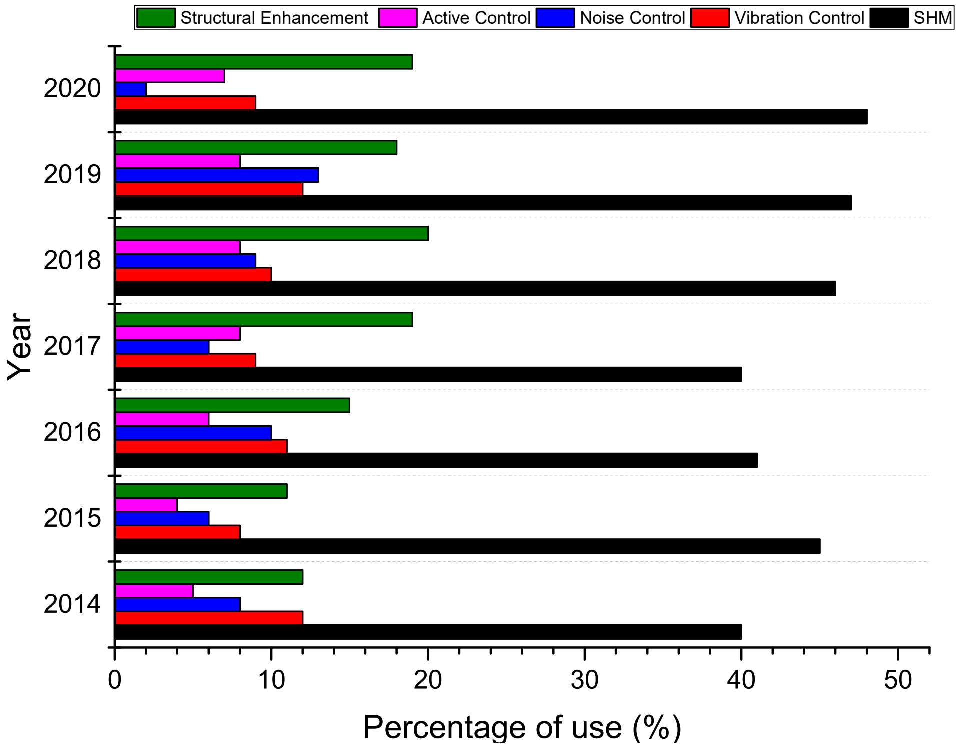

Figure 10. Trends in piezoelectric research.

Most of the previous works related to dynamic reactions of piezoelectric coupled systems with open-circuit electrical boundary conditions were performed using FE simulations. All previous repair techniques have been extended to thin beams and plate systems. There is no mathematical or theoretical model for the structural repair of piezoelectric materials that provides an active feedback control mechanism for multiple damages to various structures. The composite laminates were used in many structural applications, involving active repair and control by specific requirements. The stress concentration at the adhesive joints can be controlled by using the piezoelectric actuator and the induced surface moment. The value of the fracture tolerance of essential damage systems and their components needs further study and the creation of innovative design solutions, according to the researchers. They say the crack tip strain is exceeding infinity at the tip of the crack, so the previous solution is more realistic. Table 1 shows a summary of previous work with limitations and opportunities based on structural control/repair.

Table 1. Summary of previous work based on the structural control/repair.

Type of Structure	Technique Adopted	Number of Piezoelectric	Focused Parameters	Remark	Reference
Simply supported and cantilever beam	Multi-domain boundary integral formulation and spring model	2 (single and multi-layered)	Displacements, electric potential, and friction coefficient	Friction contact does not affect the repairing mechanism	[78]
Graphite/epoxy plate	wavelet-based signal processing	16	Piezoelectric patches and delamination size	Simple and needs minimum interaction	[74]
Cantilever and simply supported beam	Euler–Bernoulli beam theory and numerical simulation	2	Delamination locations, shear stress, and voltage	Piezoelectric materials are capable of repair of delaminated beam	[4]
Cantilever model	FE analysis using ANSYS	2 (single and multi-layered)	Crack location and length, repair voltage, patch thickness, and length	FEM analysis allows a detailed understanding of active repairs as well	[75]
Beam	FEM analysis using ABAQUS	2 (top and bottom)	Repair voltage, repair index,	The repair index depends upon the delamination location	[76]
Cantilever beam	Multi-domain boundary integral formulation and spring model	2 (single and multi-layered)	Shear stress, peal stress, crack displacement	The piezoelectric patch actuation capacity decreases due to shear stress transfer at the interface of structure and crack	[6]
Composite (drop ply) and cantilever beam	Springle model and multi-domain boundary integral formulation	2 (single and multi-layered)	Total ERR distribution, normal and tangential crack surface displacements	The optimal position for the patch is on the top of the skin, which eliminates crack opening.	[77]
Rectangular plate	Stiffness ratio and induce strain	2 (top/bottom)2 (left/right) around a circular hole	Reduction of stress concentration factor	SIF	[62]
Aluminum alloy 2024-T3 and 7075-T6 plate	J-integral using the FE method	1 composite patch (carbon/epoxy)	Crack propagation	Parametric study and SIF with experimentation give more ideas	[152]
Aluminum 2024-T3 plate	Von-mises stress, J-integral using FE analysis	1 compsite patch (boron/epoxy)	Fatigue life	SIF	[153]
GH2036 superalloy (novel model)	low and high cycle fatigue loading	No patch	crack closure and behavior of growth	Reproduce with bonded composite patches and piezoelectric actuators	[154]
Aluminum plate	Step heating thermography with FE modeling	1 (Composite patch)	delamination and disbond) with thermal heat transfer	SIF	[155]

6. Conclusions

Based on the present investigations, some conclusions have been made:

- The procedure of control and repair used to preserve the structural integrity of damaged components is distinctive. It is established on the converse piezoelectric effect, in

which the local moment and force induced in the piezoelectric materials by an applied electric field would make it easier for the structure to prevent the development of high stress and strain levels because of external load and thus lessens the criticality of the damage.
- Structural health monitoring is also proving highly significant in avoiding the premature collapse of structures based on aerospace and civil industries such as offshore platforms, houses, bridges, and underground structures.

In this review, guidelines for scientists attempting to apply piezoelectric actuators/sensors in engineering structures are introduced. These guidelines include descriptions, findings, and analysis of the critical literature of piezoelectric material applications. A brief idea of the research areas of piezoelectric material can be presented in the classification. Furthermore, researchers may give transparent views and indices for their research areas through the challenges and opportunities. In short, these guidelines can help researchers to develop new ideas, particularly in the early stages of this research field.

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