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ARTICLE

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PIEZO-BASED TECHNIQUES FOR CORROSION DETECTION AND OVERALL HEALTH MONITORING OF AEROSPACE STRUCTURES

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Corrosion poses a significant threat to aerospace structures, leading to safety hazards and operational failures. This review briefly discusses the state of art in corrosion monitoring techniques, focusing on the significance of piezoelectric transducer-based structural health monitoring (SHM) technologies and their applications in the aerospace industry. Based on the recent studies, we find that the piezoelectric material-based techniques are superior among the other methods in terms of their efficiency, cost-effectiveness, and structural simplicity. The importance of structural health monitoring and the role of advanced sensors in mitigating corrosion risks are highlighted.

Keywords: *Piezoelectric Sensors, Corrosion detection, Ultrasonic Transducer, Acoustic Emission, Lamb wave, Structural Health Monitoring*

Introduction

The irreversible electrochemical reaction of materials with their environment usually leads to the degradation of the material, causing corrosion. Galvanic corrosion (bimetallic corrosion), erosion-corrosion, crevice corrosion, pitting corrosion, stress corrosion, hydrogen embrittlement, and intergranular corrosion, etc., are examples of various types of corrosion. Corrosion hinders the proper functioning of the materials and often causes abrupt failures. Hence, corrosion control and prevention are significant concerns of multiple industries to guarantee good fatigue life for the manufactured industrial objects. As per the report in 2015, the Indian annual expenditure for corrosion control of infrastructure, industrial equipment, and other vital installations is Rs 2 trillion (USD 40 billion). It reveals the role of corrosion in eating up the Indian economy[1]. More importantly, corroded objects cause safety issues, especially in the aerospace industry, where the slightest negligence causes severe operational failures and engine destructions. For example, in 1988, an unattended corrosion caused Aloha Airlines 737 to lose its upper half of the fuselage during a flight at 24000 ft. high.

Unattended corrosion poses a significant risk across industries, necessitating proactive measures for mitigation. In aerospace, where early detection of corrosion is challenging yet critical, understanding its causes and employing proper remedial strategies is paramount. Corrosion, often initiated by moisture penetration, can lead to surface pitting and subsequent crack formation under mechanical stress, reducing equipment lifespan. Aerospace structures, exposed to harsh environmental conditions, are particularly vulnerable, making early detection and prevention crucial to ensuring safety and reliability. Effective corrosion detection techniques are essential for maintaining structural integrity and minimizing the risk of catastrophic failures, underscoring the importance of advanced non-destructive monitoring methods for prolonged service life and reduced maintenance costs[2].

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Various Corrosion Monitoring and Detection Techniques

Various techniques are employed for corrosion monitoring, ranging from traditional methods to advanced technologies that offer real-time insights into the corrosion processes. The advancement of SHM techniques depends on the progress of multiple fields, including sensor technology, signal processing, digital twin modelling, optimization methods, data analysis, and machine learning algorithms[2,3]. In a broad sense, we can classify the SHM techniques into three categories. One is based on the routine visual inspection of the equipment at regular intervals using techniques such as infrared imaging, colour visual imaging, electrochemical impedance spectroscopy, eddy current, radiography, etc. Though Visual inspection remains a fundamental approach, allowing for the direct observation of corrosion-related damage on surfaces, however, visual inspection may not always be sufficient for detecting hidden corrosion or assessing the extent of damage in complex structures.

The second category is the in-situ sensors incorporated with the structural health monitoring, based on sensing various stimuli such as pH, humidity, ion concentration, chemical potential, etc. In the final category, the attached corrosion detectors undergo the same chemical process that the structure is experiencing. Here, the mass loss of the attached corrosion coupon is investigated to measure the corrosion rate in the structure[4]. The complexities associated with this method include the installation of coupons at corrosion investigation sites and periodic in-lab complex checking for the weight loss of installed coupons. Consequently, the corrosion coupon technique[5] is unsuitable for online corrosion monitoring, making it a costly and time-consuming conventional approach. The online corrosion monitoring is of two types, intrusive and non-intrusive. The intrusive methods such as linear polarization resistance measurement[6,7] and weight measurement [7,8] require constant contact with the corrosive substance. In contrast, the non-intrusive method does not require constant direct contact with the material under inspection[9,10]. In the next section, we will discuss about piezo-based corrosion monitoring and detection techniques, with a specific emphasis on their role in the aerospace industry.

Piezoelectric Material-based Corrosion Detection and Structural Health Monitoring

Structural Health Monitoring is very essential in all sectors to increase fatigue life and structural integrity[11,12]. Though there exist several advanced technologies in SHM, finding the most efficient, non-destructive, reliable, inexpensive, rapid, and sensitive technique for real-time practical applications is difficult. Thankfully, many disadvantages of the conventional aforesaid techniques can be resolved by integrating smart materials such as piezoelectric materials into the scanning devices. Piezoelectric materials have emerged as a promising solution for corrosion detection and structural health monitoring due to their efficiency, non-destructive nature, reliability, and cost-effectiveness. By incorporating smart materials like piezoelectric sensors, a new trend in corrosion detection has been established, overcoming the limitations of traditional techniques. The direct and indirect piezoelectric effects enable piezo-sensor-based SHM techniques to respond to external stress and electrical stimuli, making them versatile. These sensors can operate through various methods, such as electromechanical impedance technology[13,14], ultrasonic propagation monitoring[15], acoustic emission[16], and stress monitoring[17]. Moreover, these technologies, developed through extensive experimentation, offers a safe operational mode with reduced maintenance costs. The other advantages of piezoelectric sensor-based SHM technology over conventional monitoring methods are their small size, lightweight, market availibility, low cost, diversified sensor technologies[2].

Electromechanical Impedance (EMI) Based Analysis

Electromechanical impedance (EMI)-based corrosion detection is a cutting-edge technology that offers efficient, non-destructive, and reliable monitoring of corrosion in aerospace structures. The corrosion-induced thickness loss causes changes in the mass, stiffness, and/or damping of the structure which results in variations in the mechanical impedance of the structure. When piezoelectric material such as PZT is bonded on the structure, the change in mechanical impedance is reflected as a change in the electrical impedance of bonded piezoelectric material[18].

The schematic of EMI analysis is given in Fig. 1. Annamdas and Soh[19] conducted a semi-analytical model study on PZT-based SHM and validated it through experiments using multiple PZT patches on a laboratory-scale aluminium plate. This method provides real-time data on structural health, enabling early detection of corrosion and enhancing the structural integrity of aerospace components. EMI-based corrosion detection is cost-effective, sensitive, and suitable for real-time practical applications, making it a valuable tool for ensuring the safety and longevity of aerospace structures. The

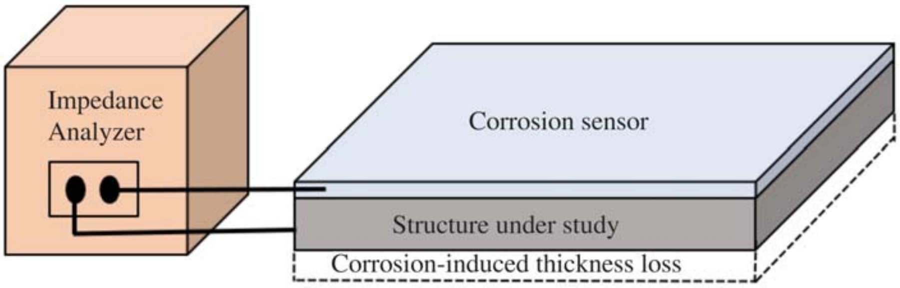

Fig. 1: Schematic of EMI-based corrosion sensing experiment.

structural damage can be determined by noting down the variation in the electrical impedance of bonded piezoelectric material from a healthy state. This approach is capable of distinguishing light surface corrosion and multiple site surface corrosions (pre-crack surface corrosions). Furthermore, this method is most suitable for detecting corrosion and pit depth[4]. The EMI of the bonded PZT sensor changes as per the corrosion-induced thickness reduction of the material under investigation. The exact identification of corrosion requires a comparative study on the sensor response in undamaged structure to the response after a specified time period[20]. W. Li et al. experimentally verified the decrement in the frequency of first transverse bending mode in association with the corrosion induced-thickness loss of the metal and the progression of corrosion is quantified through the manipulation of obtained decrement. The findings are verified through finite element analysis (FEA) too[21].

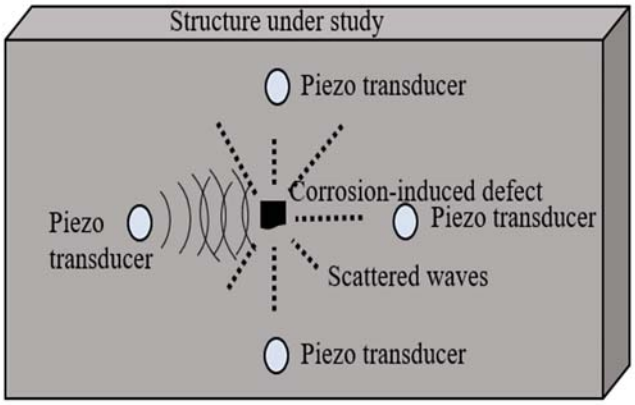

Fig. 2: Schematic of ultrasonic transducer array-based damage detection experiment.

A thin piezoelectric wafer sensor is also reported to have detected the corrosion on aluminium 6061 alloys through EMI analysis. The corrosion growth is monitored by utilizing the variations in the real part of electromechanical impedance generated on the piezoelectric sensor in response to the induced corrosion in the NaOH environment. This approach is capable of an effective quantification and detection of early-stage corrosion on aluminium. The reported optimum detection distance is 15mm from the sensor[22].

Ultrasonic Lamb Wave and Transducer-based Techniques

Ultrasonic Lamb wave and transducer-based techniques are advanced methods used in aerospace for non-intrusive corrosion monitoring [9,10,23,24]. In the Lamb wave method, the highly dispersive

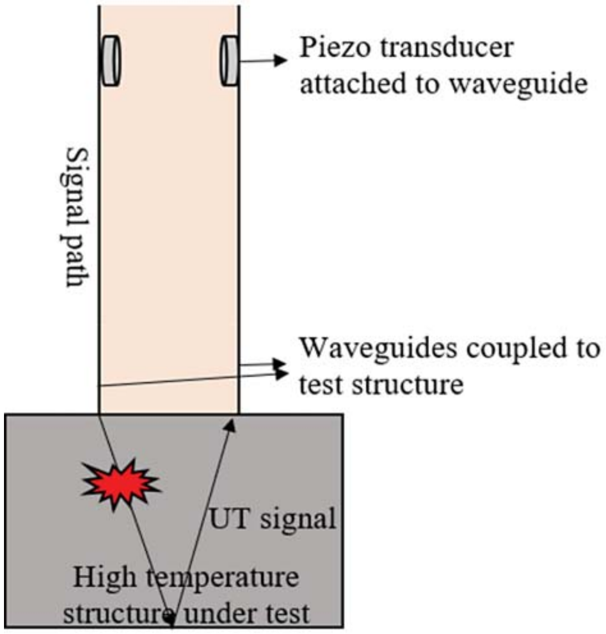

Fig. 3: Schematic of the waveguide thickness gauge.

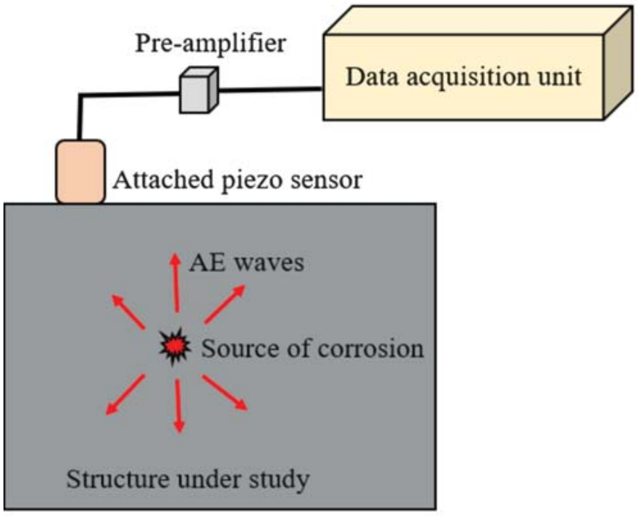

Fig. 4: Schematic of the experimental set-up of acoustic emission-based corrosion monitoring.

ultrasonic Lamb waves of normally low frequency are released from the piezoelectric transducer that is embedded or mounted into/on the structure[25]. It then propagates through the material under study. The corrosion-induced effects in the material scatter the ultrasonic waves, which are later detected by the transducer. The defects in the structure are identified by analysing this deflected signal. The exact location of structural damage can be realized with the help of an array of piezoelectric transducers which notes down the received time of the deflected signal. Knowing the velocity of the wave in the structure, this information is used to extract the damage location. A schematic of ultrasonic transducer array-based damage location detection is given in Fig. 2. The advantages of this method include large inspection areas, multi-mode capabilities, and the ability to detect corrosion in curved structures. However, challenges such as beam spread and scattering can limit the testing range. To reduce the undesired scattering, low-frequency testing to that of global structural vibration is suggested. The beam spread-induced attenuation can be minimized by modal analysis that employs a standing wave, for condition monitoring. This is achieved by using piezoelectric actuators over electromechanical actuators since they generate vibrations whose amplitude is much smaller. Hence only very low energy is required to induce in the structure. The corrosion detection capability of Lamb waves, guided ultrasonic waves, through corrosion-induced material loss investigation is reported by Alleyne and Cawley in 1992[26]. The concept of Lamb wave signal transmission along the back of the experimenting plate is proposed by Sicard et al. to monitor the hidden corrosion in aircraft structures[27].

The complications in elevated temperature applications of piezoelectric transducers are resolved by the arrival of the high-temperature ultrasonic thickness gauges, in which the temperature-sensitive piezoelectric and transducer elements are intentionally kept out of high-temperature measurement region through a long waveguide of rectangular cross-section that is clamped to the

Table 1: Comparison of piezo-based corrosion detection techniques

Corrosion Detection Technique	Advantages	Disadvantages
Electromechanical Impedance (EMI)	● High sensitivity and non-destructive monitoring capabilities ● Cost-effective and efficient for corrosion detection ● Remote and autonomous monitoring capability ● Rapid response ● Real-time monitoring and easy installation[18]	Limited detection range depending on sensor placement
Ultrasonic Lamb Wave Techniques	● Non-intrusive method for online corrosion monitoring ● Effective for complex materials and large inspection areas[2]	Beam spread and scattering can lead to attenuation and reduced testing range
Piezoelectric Wafer Active Sensors (PWAS) and Guided Lamb Waves	● Non-destructive testing method for corrosion detection ● Large inspection area coverage and ability to detect hidden corrosion ● High sensitivity to thickness changes ● Real-time monitoring capability ● Early detection of corrosion	Limited by beam spread and attenuation, reducing testing range
Modern Acoustic Emission (MAE)	● Accurate detection of corrosion-induced signals in aircraft components ● Repeatability and reliability in corrosion monitoring	Equipment cost and complexity may be higher compared to other methods
Micro-electro-mechanical Systems (MEMS)	● Compact and efficient sensors for corrosion detection ● Lightweight and low-power consumption for aerospace applications	Require specialized expertise for integration and calibration

inspection element (Fig. 3). The best transmission and reception of ultrasonic waves through the waveguide is noted in anti-plane shear loading, making the proposed system follow a non-dispersive guided wave mode. This method of permanently installing point thickness gauges to measure the average thickness loss over a modest area is one of the reliable and efficient SHM today[28]. Active health monitoring in aircraft wings using embedded piezoelectric sensor/actuator network is presented by Zhao et al. in 2007 by making use of guided wave piezoelectric (PZT) sensors/actuators. The wave propagation capabilities are first understood by experimenting with angle-beam Lamb wave transducers on wing panels and found that the inspection range reduces as the attenuations and scattering from the paint and rivet rows increase. The ultrasonic guided wave is produced on the structure by bonding a relatively sparse PZT array of 30 cm diameter on the inner surface of the wing. The receptions of thus generated guided waves are also taken up by the same PZT array. An algorithm called RAPID is used to study the correlation when defects like loose rivets, cracks, and material loss are introduced in the wing panel. This method facilitates an accurate measurement in defect detection, localization, and growth monitoring[29]. Flexible integrated piezoelectric ultrasonic transducers are later identified to have application in the in-situ monitoring of ice and structure thickness. They can be simultaneously applied in in-flight ice thickness measurement and the monitoring of ice conditions at many critical locations. For aircraft-based applications, piezoelectric film-based sensors were fabricated through the sol-gel spray technique which functions at operating temperature 80°C to 100°C. The study is verified by integrating an ultrasonic piezoelectric film transducer (thickness>40 μm) that is deposited on the interior of a 1.3 mm thick aluminium alloy stabilizer of the aircraft wing structure. The second type of flexible ultrasonic transducer which is fabricated by coating piezoelectric films onto a 50 μm thick polyimide membrane also measured the thickness of the stabilizer outer skin and ice. The most accurate stabilizer outer skin thickness reported by this method under constant temperature is 41 μm[30]. Proposed for other aerospace applications, ultrasonic wheel-array sensor scanning systems feature a 64-element transducer array encased in a fluid-filled wheel, operating at 10 MHz to minimize acoustic losses. Constructed from a soft, durable polymer, the wheel interfaces with dry/liquid-filled test structures to generate real-time defect maps (C-scans) as it rolls over surfaces. These sensors find utility in detecting embedded defects in thick carbon composite blocks, identifying cracking and disbanding in composite skin-stringer samples, and monitoring sealant layers in aluminium aircraft wing structures[31]. Zhao et al.[29] introduced wireless ultrasonic methods for structural health monitoring of aircraft wings. Utilizing piezoelectric (PZT) disc transducers bonded at various wing locations, defects are detected, localized, and monitored through ultrasonic guided waves. While one method employs reactive coupling monopoles for wave generation and reception, signal noise and proximity constraints are noted drawbacks. A second wireless approach involves embedding a diagnostic device into the wing, capable of transmitting frequency-modulated digital signals powered wirelessly by an antenna-rectifier array on the aircraft body, thus eliminating battery replacement concerns. Testing with PZT sensor arrays on wing panels[32] validates the efficacy of the wireless system. Overall, ultrasonic Lamb wave and transducer-based corrosion detection offer a valuable tool for enhancing the safety and reliability of aerospace structures.

Piezoelectric Wafer Active Sensors (PWAS)

Piezoelectric wafer active sensors (PWAS) represent a cutting-edge technology utilized in aerospace for corrosion monitoring and structural health assessment. These compact, cost-effective, and minimally intrusive sensors leverage Lamb wave techniques to identify defects and damage within aerospace structures. PWAS offer several advantages, including straightforward attachment to structures, deployment in sensor arrays, and integration with data concentrators and wireless communicators. They have demonstrated effectiveness in detecting impact damage, delamination, and corrosion in composite materials, underscoring their significance in aerospace applications.

Keilers and Chang in 1995 demonstrated an in-situ piezoelectric technique to monitor material damage through wave propagation. The experiment was later extended to delamination damage identification in composite plates by Wang and Chang. The pitch- catch mode operation of four piezoelectric wafer transducers delivered the detection of impact damage in composite structures. The advantages of Lamb wave techniques over frequency response methods in local damage sensitivity were elucidated by the experiments of Kessler et al. on composite structures.

A theoretical model for PWAS analysis was proposed by Xu and Giurgiutiu in 2007 in their paper, Single-mode tuning effects on Lamb wave reversal with piezoelectric wafer active sensors for structural health monitoring. The existence of single-mode Lamb waves was first studied and validated experimentally by the theoretical model. A numerical model is then used to study the time-reversal

Table 2: Comparison of the piezoelectric technique against other traditional and modern methods of corrosion detection in terms of sensitivity, cost, and ease of implementation

Method	Sensitivity	Cost	Ease of implementation
Piezoelectric	Extremely sensitive to mechanical changes brought on by corrosion-induced strain and stress. They are useful for early-stage detection and real-time monitoring because they can identify early indications of corrosion by tracking the way the structure reacts to stress. Piezoelectric sensors used for electromechanical impedance (EMI) and guided ultrasonic waves (GUW) techniques are considered to be superior due to their mechanical to electrical conversion efficiency i.e., coupling coefficient.	Piezo sensors are widely marketized and they are very cheap as per the cost is concerned. However, the installation (especially embedding in structures) can increase expenses, particularly in complex aerospace environments. Relatively low maintenance and long-term monitoring costs, compared to traditional methods requiring frequent inspections.	Relatively easy for surface-mounted applications. They do not require a lot of changes to be adapted into existing constructions. Embedding/integrating them into aircraft structures pose some complexity in terms of routing the wire especially for aerospace applications but technological advances such as direct printing/painting on the structure could drastically simplify the process. Real-time data from piezoelectric devices allows continuous health monitoring with little need for human intervention.
Traditional Methods (Visual Inspection, Ultrasonic Testing, Radiography, etc.)	Lower sensitivity in detecting early-stage corrosion. Subsurface corrosion may go undetected by conventional ultrasonic testing, and visual inspection typically only finds corrosion that is readily apparent. Radiography is less effective for continuous monitoring, although it is quite sensitive for identifying interior corrosion.	The least expensive option is visual inspection, although its sensitivity and accuracy are limited. The implementing cost of techniques like as radiography and ultrasonic testing are higher because of huge initial investment cost of equipment. Additionally, these techniques necessitate recurring inspections, which raises overall expenses.	Simple ultrasonic testing and visual inspection are easy to do but laborious job and extensive manual interventions required. Continuous monitoring is less convenient with radiography since it needs specialised equipment and it can interfere with operations during inspection.
Modern methods (Electrochemical Impedance Spectroscopy, Fiber-Optic Sensors)	Although electrochemical impedance spectroscopy (EIS) is usually limited to localised observations, it is particularly sensitive to early corrosion at the molecular level. Although they can be more difficult to implement, fiber-optic sensors have higher sensitivity and are less susceptible to electromagnetic interference.	The specialised equipment for electrochemical and fiber-optic sensors are typically more expensive. The process of installation and calibration of these systems are intricate and expensive.	Installing fiber-optic and electrochemical sensors can be challenging, particularly in large or complicated structures like aircraft, and they frequently need to be calibrated precisely. Once deployed, they offer extremely accurate data, but their operation may need frequent maintenance.

behaviour of single and two-mode Lamb waves. This technique has the advantage of monitoring damages even in the absence of baseline data. The existence of at least two Lamb wave modes at any frequency and the dispersion of Lamb wave modes in thin-wall structures are the two complications associated with this technique[33].

A piezoelectric wafer active sensor approach, using far-field wave propagation along with near field electromechanical impedance, to detect damages in aging aircraft is proposed by Giurgiutiu et al. in 2002. This simultaneous use could bring complete coverage of the monitored structure. Proper tuning of the signal processing method and damage-metric algorithm with specific structural interrogation techniques is required. The presence of damage is detected in the high-frequency electromechanical impedance method by comparing the pattern recognition methods with the impedance signature that varies according to the damage. In the wave propagation approach, the reflection of the propagating wave from damages causes changes in the phase and velocity of the wave. This change is analyzed in monitoring defects in the structure[34].

Specifically, in corrosion detection on aircraft skins, PWAS are configured in a pitch-catch arrangement with embedded transducers arranged in a grid pattern permanently affixed to the structure. One PWAS transmitter sends Lamb waves into the material while another PWAS in the grid detects these waves. Changes in the Lamb wave propagation indicate corrosion presence. Various methods can be employed for corrosion monitoring, including direct signal correlation, wavelet transform analysis, Hilbert transform for signal envelope comparison, and neural network correlation between transmitted and received signals. Above all, the quantification of damages based on different corrosion depths and intensity is crucial[35].

Acoustic Emission (AE) Based Analysis

Acoustic emissions are generated in a structure when random chemical reactions occur anywhere in the structure. These emissions are generally of low energy and short duration. A similar release of acoustic emission is observed when a crack propagates/ multiple micro- fractures are formed/de-lamination occurs. Compared to crack growth, the acoustic emission due to corrosion is weak, resulting in detection difficulty in the field environment. Acoustic emission (AE) monitoring detects structural changes, such as crack propagation or corrosion, through low-energy, short-duration emissions. While corrosion-induced AE is weaker, it's detectable with piezoelectric sensors. This non-intrusive, cost-effective method allows real-time, continuous monitoring of active corrosion, both locally and globally, without external signals. However, challenges include background noise interference and soundwave distortion during travel. The experimental setup requires a piezoelectric sensor to be attached to the structure under study to detect the acoustic emission released as a result of corrosion (Fig. 4).

While traditional acoustic emission (AE) methods offer easy, low-cost corrosion monitoring in aviation, identifying the root cause of AE sources can be challenging. Modern acoustic emission (MAE) techniques, as described by Geng. R in 2006, address this issue by combining AE parameters and waveform analysis. MAE accurately locates AE sources using digital instruments with low noise and rapid data transmission. It involves data trend analysis, correlation, and advanced processing, based on classical Lamb wave theory. Despite being costlier and more time-consuming, MAE excels in repeatability and accuracy. Corrosion-induced AE signals are characterized by burst-type emissions and a wide frequency range (20 kHz to 500 kHz), with flexural waves below 100 kHz and extensional waves above. The time difference between the output signals from different transducers helps in identifying the sound velocity[36].

Micro-Electro-Mechanical-Systems (MEMS)

The piezoelectric-based corrosion detection and other damage detection techniques offer advantages of compact design due to its small size. However, the brittleness of piezoelectric ceramics is a drawback. This limitation can be resolved by utilizing piezoelectric materials in Microelectromechanical systems (MEMS), offering benefits such as lightweight, low power consumption, compact size, tunability, low cost, and compatibility with microfluidics and micro-optics.

The role of MEMS in the aircraft industry is inevitable. The smart skin integration, by combining standard microelectronics and micromachining with novel smart electronics or wireless communication systems for structural health monitoring of aircraft is reported elsewhere. Such smart skins are reported to have multifunctional utilities such as drag sensing and control, ice sensing and anti-icing, noise sensing and control, vibration sensing and control, structural integrity monitoring of aircraft, monitoring fatigue cracking, corrosion, impact damage, and delamination, monitoring location and propagation of cracks, the quality of conventional bonds and "kissing bonds" in composite structures, detecting deflection and strain of aircraft structures, wings, and rotor blades[37].

A summary of all the piezo based techniques, along with a comparison of the piezoelectric technique against other traditional and modern methods of corrosion detection in terms of sensitivity, cost, and ease of implementation is provided in Table 1 and 2 for adequate reference.

Challenges and Potential Areas for Future Research

While piezoelectric sensors are indispensable for SHM, there is still room for improvement in current piezo-based corrosion detection techniques by addressing existing challenges. To enhance the accuracy and reliability of these techniques, the development of highly sensitive piezo materials is crucial. This requires novel materials with exceptional piezoelectric properties. While piezo composites can mitigate some limitations of organic and inorganic systems—such as low piezoelectric coefficients and limited flexibility—there remain opportunities to improve their performance, particularly in harsh environments and under high mechanical loads which is commonly encountered in aerospace applications.

Advancing novel material processing technologies like 3D printing is essential to overcome the complexities of integrating piezo-sensors—whether ceramic, polymer, or composite—into aircraft structures. While numerous experiments demonstrate the effectiveness of piezo-based techniques for corrosion monitoring in aircraft, still significant challenges remain. These include addressing practical issues such as sensor self-detection, non-linearity, impact of environmental changes, and the detection of fundamental structural failure modes. Overcoming these technical issues open up more avenues for practical applications of piezo-sensors[2]. Furthermore, techniques for self-diagnosis of sensor failures[38-40] are essential to improve the reliability of the piezo-based SHM technique in aerospace industry[41].

Conclusions

This report discusses the state of art Piezo-based corrosion and other damage detection techniques for the health monitoring of aerospace structures**.** Based on our studies, we find that the piezoelectric material-based techniques are superior among the other methods in terms of their efficiency, cost-effectiveness, and structural simplicity. Since, a combined approach of impedance and wave propagation technique showed promising results in corrosion monitoring, further investigation on these areas would be beneficial. Similarly, the signal processing side of the impedance method has to be explored in the future. The current approach of impedance response chart and damage metric chart need to be statistically analyzed using some difficult algorithms. Hence future work should focus to investigate the use of pattern recognition methods that will capitalize on the features of the impedance signal for more successful damage detection. ❐

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