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Structural Health Monitoring Method Regarding a Multi-Sensor

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Abstract: *Structural Health Monitoring (SHM) involves the continuous monitoring of a structure's condition during operation using integrated sensor systems. SHM holds great promise for enhancing structural safety while simultaneously reducing deadweight and downtime. Various SHM methods have been developed to detect and evaluate different types of damage across a wide range of structures. Recently, the concept of Information Fusion combining data from multiple SHM methods has gained traction for improving damage assessment accuracy and reliability.*

Keywords: Multi-modal sensor, Sensor fusion, Hybrid material, Metallic element, EMI method, Ultrasonic wave, EIT, Carbon nanofiber, Stress-strain monitoring

I. INTRODUCTION

Modern industries, especially in transportation, face increasing demands to create lightweight, highly optimized structures. Reducing a vehicle's weight and downtime is crucial to improve efficiency while ensuring maximum structural reliability. However, uncertainties—such as actual loading conditions, material properties, environmental factors, and even misuse—often lead to over-designed structures and frequent safety inspections, resulting in operational downtime

To address these challenges, **Structural Health Monitoring (SHM)** was introduced in the 1990s as an advancement of **Non-Destructive Testing (NDT)** [1]. SHM involves continuously monitoring a structure during its operation using integrated sensor systems

This approach allows for real-time assessment of structural health. SHM capabilities are categorized into five levels [2]:

Level 1: Damage detection

Level 2: Damage localization

Level 3: Damage quantification

Level 4: Damage characterization

Level 5: Structural integrity assessment

Current SHM methods can achieve Levels 1 through 4 with relative ease. However, advancing from scheduled, inspection-based maintenance to a condition-based or predictive maintenance system requires the ability to assess structural integrity (Level 5). So far, Level 5 remains mostly conceptual, with few practical implementations [3,4].

This framework integrates the following key components:

1. Application of SHM, along with load and usage monitoring, to detect and track flaws.
2. Structural analysis to evaluate the effects of flaws on functionality and strength.
3. Implementation of condition- and prediction-based maintenance strategies in compliance with safety and regulatory standards.

This article Researchs SHM methods, focusing on their systematic combination and interdisciplinary advantages.

1.1 SHM Methods and Their Classification

Various physical principles are used in SHM to evaluate potential damage. SHM methods can be categorized as:

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a. Active methods: The structure is intentionally stimulated, and its response is measured (e.g., guided wave techniques [5,6,7,8]).
b. Passive methods: Signals generated by operational loads or damage events are monitored directly (e.g., Structural sound [9])
Additionally, SHM methods can be further divided into:
a. Static methods: Evaluating steady-state conditions (e.g., neutral axis method [10] or electrical impedance tomography [11].
b. Dynamic methods**: Monitoring changes over time (e.g., electromechanical impedance techniques [2].

1.2. Challenges and the Need for Multi-Sensor Fusion

No single SHM method can effectively detect all types of damage in every location of a structure [20]. Each method is better suited to specific damage types and structural properties. Thus, combining various SHM methods leads to more accurate and reliable evaluations [20]. Additionally, environmental factors can introduce uncertainties, requiring compensation or identification.
To address these limitations, **multi-sensor Information Fusion** has gained significant attention. Multi-sensor fusion combines information from multiple sensors to enhance accuracy. It can involve:
a. Homogeneous Information Fusion**: Using data from the same type of sensor and physical principle (e.g., guided wave triangulation with multiple transducers [19]).
b. Heterogeneous Information Fusion**: Integrating data from different types of sensors and principles (e.g., combining neutral axis identification with temperature compensation using a Kalman filter [10]).

II. INFORMATION FUSION OVERVIEW

Information Fusion techniques integrate data from multiple sensors with information from an associated database, enabling more comprehensive conclusions about potential damage than a single sensor could provide. For example, fusing three guided wave Time-of-Flight (ToF) features can help localize damage more accurately [19]. These techniques also enhance the reliability and precision of damage assessments
Information Fusion can be implemented at three distinct levels :

1. Raw Information Fusion Level: At this level, multi-sensor data is directly processed or combined to derive sensitive features that aid in detecting, localizing, quantifying, or categorizing damage. This approach is suitable when sensors measure the same physical phenomenon, often using classic detection and estimation techniques such as the Kalman filter.
2. Feature Information Fusion Level: Here, various representative damage indicators—extracted from multi-sensor data and corresponding to different damage features—are compiled into a vector. This vector is analyzed using techniques such as neural networks, clustering algorithms, or template-based methods for pattern recognition.
3. Decision-Level Fusion: This involves synthesizing evaluation results from different damage assessment methods to make informed decisions about the implications of the damage. Techniques such as weighted decision methods (e.g., voting), classical inference, Bayesian inference, or evidence theory (like the Dempster–Shafer method) are employed for this purpose.

Damage is detected by observing its effects on specific structural properties. Selecting optimal SHM methods requires a deep understanding of the structural properties most affected by the targeted damage types. Achieving this necessitates a detailed analysis of the interaction between the structure and the damage.
Table 1 presents an overview, based on insights from existing literature and the authors' expertise, detailing various types of damage observed in metal and composite structures and their qualitative impact on local mechanical properties. The metals examined include aluminum alloys, titanium alloys, and steels. The composite materials considered are primarily laminated carbon fiber-reinforced polymers (CFRPs) and glass fiber-reinforced polymers (GFRPs).

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Material	Damage Type	Material Stiffness E	Mass m	Damping c	Material Conductivity σ	Boundary Formation a
metal	notch	∘	−	−	+	+
	crack	+	−	−	+	+
	corrosion	∘	∘	∘	∘	∘
composite	notch	∘	−	−	+	+
	matrix crack	∘	−	∘	∘	−
	fiber crack	+	−	∘	+	−
	delamination	∘	−	∘	∘	+

III. FUNDAMENTAL SHM METHODS

For the development of an effective multi-sensor SHM approach for a specific structure and its potential damages, it is essential to understand the capabilities of various standalone SHM methods. The capabilities are largely influenced by the governing equations of the methods and the sensitivity of their physical parameters to damage. However, it is not only necessary to identify the most sensitive approach, but also one that is robust enough to handle uncertain environmental influences. Below, a brief overview of some of the most common SHM methods is provided, highlighting their capabilities and limitations.

3.1. Static Strain Measurements with Fiber Optical Sensors (FOS)

The measurement of strain to assess a structure's mechanical behavior has been used for decades [4]. Strain-based techniques, owing to their local nature, have traditionally been employed for fatigue monitoring in areas of known stress concentration on a structure. The most common sensor for such applications is the strain gauge. In recent years, however, the development of fiber optical sensors (FOS) has expanded the scope of strain measurement applications. FOS technology offers significant advantages, including high sensitivity, immunity to electromagnetic interference, durability, multiplexing capabilities, and the potential for embedded sensing, making it a promising tool for continuous real-time monitoring of structures like aircraft [13].

Strain-based SHM approaches can be categorized into techniques operating in the frequency domain and the time domain. Static strain measurements fall under the time-domain category. Time-domain techniques include rain-flow counting algorithms for fatigue monitoring and other methods for measuring local strain in known hotspots For broader structural monitoring, the use of neural networks and machine learning algorithms is becoming increasingly popular to analyze the relationships between strain sensors located at different points [14]. A significant deviation between the strain predicted by a model and the measured strain can indicate potential damage. Thus, strain measurements are effective for assessing any damage that alters the local load path (strain state) of a structure under given loading conditions, such as cracks in composite or metal components, or residual strains following a damaging event, like impact or plastic deformation.

However, certain types of damage are challenging to detect with static strain measurements. For example, delaminating caused by manufacturing defects may only affect the strain state under high loads, which causes the delaminating to buckle, making it difficult to detect under normal loading conditions. While a sufficiently dense sensor array can enable damage detection, localization, and size estimation, identifying the damage type (SHM Level 4) has not yet been reliably demonstrated.

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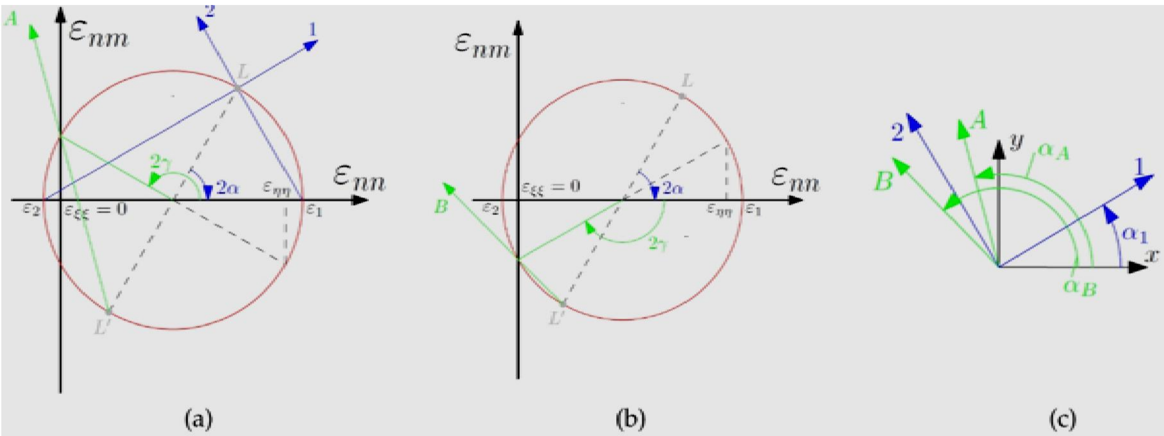
To optimize strain-based SHM using a small sensor array, sensitive damage assessment indicators, such as the neutral axis location [36] or the zero-strain trajectory (ZST) are needed. The ZST method, developed by the authors' research group, uses strain measurements along designated zero-strain trajectories as damage-sensitive indicators for structural assessment.



3.2. Vibration Analyses with Electro-Mechanical Impedance Method

The Electro-Mechanical Impedance (EMI) method is a vibration-based technique widely used for structural health monitoring (SHM). This approach utilizes one or more piezoelectric wafer active sensors (PWAS) attached to the mechanical structure of interest. The PWAS serves both to excite the structure and to measure its frequency response in the form of impedance, which is the ratio of applied voltage to measured current:

$$Z(\omega) = \frac{U(\omega)}{I(\omega)} ,$$

Here,U(\omega) is the amplitude of the applied harmonic voltage, and I(\omega) is the resulting current at the PWAS for different angular frequencies (omega = 2pif). The impedance Z(omega) provides valuable insight into the mechanical structure's condition because changes in impedance are indicative of changes in the structural properties, such as damage.

$$Z(\omega) = \frac{1}{j\omega C}\left(1 - \kappa_{31}^{2}\frac{k_{\mathrm{dyn}}(\omega)}{k_{\mathrm{p}} + k_{\mathrm{dyn}}(\omega)}\right)^{-1}$$

In the one-dimensional case, neglecting the damping and dynamics of the PWAS, the relationship between the measured impedance and the structure's dynamic response can be expressed as:

$$k_{\mathrm{dyn}}(\omega) = -m\omega^2 + jc\omega + k_{\mathrm{stat}} ,$$

Where:
m is the mass,
c is the damping coefficient,
k is the static stiffness of the structure.

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The EMI method, along with other vibration-based SHM techniques, is sensitive to changes in structural properties such as stiffness, mass, damping, and geometry, making it applicable to a wide range of damage types in both metallic and composite structures.

However, due to the numerous structural properties involved and their sensitivity to environmental influences, unique damage assessment can be challenging. Predicting structural vibration, especially for high-frequency vibrations required to detect small damages, is difficult, particularly with methods like Finite Element Analysis (FEA), which may not accurately capture high-frequency behavior.

To mitigate these challenges, EMI-based SHM is generally implemented in two steps:

1. Baseline Measurement: The impedance spectra of the pristine structure are measured over a wide frequency range.
2. Continuous Monitoring: The impedance spectra are continuously monitored and compared with the baseline measurement throughout the structure's operational life.

Any deviations in the impedance Z or admittance $Y = \frac{1}{Z}$ characteristics are used as damage indicators. These deviations can indicate the presence of damage and also assist in self-diagnosis of the PWAS transducer, such as detecting changes in its capacity (ΔC) or resonance frequencies, which are useful for monitoring PWAS-structure bonding integrity【20】.

Damage Detection and Localization:

For damage detection (SHM Level 1), basic statistical damage metrics are used to compare the impedance at the current state of the structure with that from the pristine state. These metrics typically focus on the real part of the impedance, such as the root-mean-square-deviation (RMSD)or mean-absolute-percentage-deviation (MAPD)【15】

These metrics can also aid in **damage localization** (SHM Level 2). Since vibration attenuation increases with distance from the PWAS transducer, the damage location can be estimated based on the attenuation functions of the impedance measurements. This allows for triangulation techniques to pinpoint the damage. For instance, an experimental setup with movable artificial damages on an aluminum plate, as shown in Figure 6, correlates the MAPD with attenuation functions. Numerical simulations can help refine these estimates for better localization accuracy, enabling more reliable damage detection at a reduced number of measurements.

3.3. Ultrasonic Guided Waves (UGW)

Ultrasonic Guided Waves (UGW) have gained significant attention in the Structural Health Monitoring (SHM) research community in recent decades. Their ability to travel long distances with minimal energy loss, particularly in thin-walled structures, makes them an attractive option for damage detection in various materials, including metals and composites【18】. These waves interact strongly with structural changes, such as cracks or delimitation, and can be used for damage assessment due to their high sensitivity and cost-efficiency【18】.

UGWs are elastic waves that are confined within a structure by its boundaries, and their classification depends on the type of deformation they induce in the material. The main types of UGWs used in SHM applications are:

1. Shear Waves (SH and SV): These waves involve motion perpendicular to the direction of propagation and exist in horizontal (SH) and vertical (SV) forms. SH waves are particularly useful for applications like underwater inspection since they experience less attenuation in liquid media.
2. Lamb Waves: These waves are confined between two parallel surfaces, such as the upper and lower surfaces of an infinite plate. For practical structural components, Lamb waves are generated when there is a large ratio of in-plane dimensions to thickness. They propagate as a superposition of symmetric and asymmetric modes, with the fundamental modes S0 (symmetric) and A0 (asymmetric) being most prominent at lower frequencies.
3. Rayleigh Waves: These waves propagate along the free surface of structures, making them useful for detecting defects close to the surface.

Lamb waves and SH waves, in particular, have the advantage of little energy loss over long distances, making them ideal for SHM in metallic and non-metallic structures. In SHM, the propagation speed and attenuation of UGWs depend on material properties (such as elasticity, density, and damping) and geometrical properties (such as wall thickness, phase transitions, micro cracks and surrface raggedness). These properties influence how the wave interacts with the

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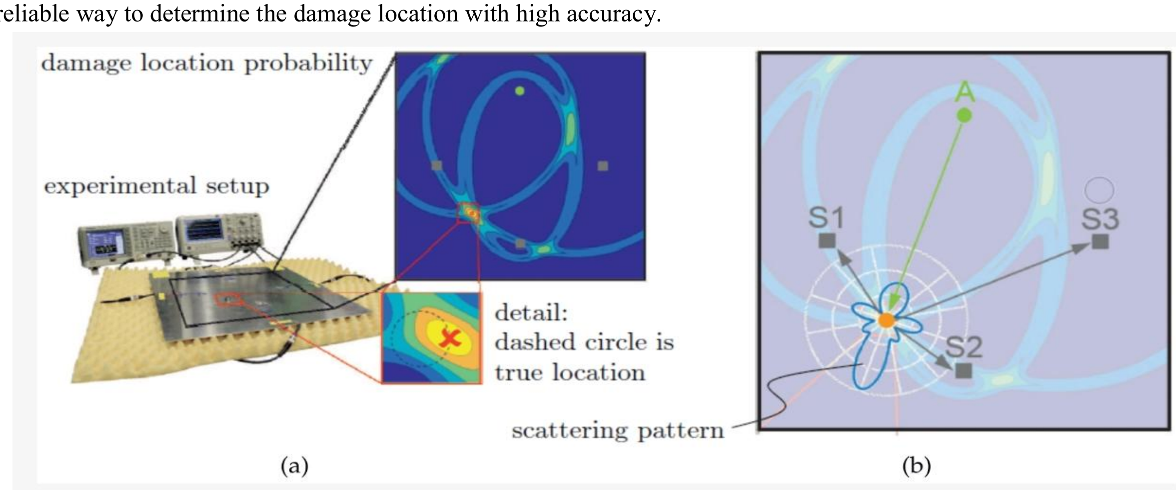
structure, allowing UGWs to be reflective of damage types like cracks or corrosion in metals, and delimitation in composites.

While UGWs offer great potential for SHM, they also have limitations. Surface coatings can lead to high attenuation, and the method is sensitive to environmental factors like temperature and moisture. Additionally, surface dirt or changes in material properties can also interfere with wave propagation, which complicates data interpretation. The high demands on experimental equipment and the challenges posed by environmental noise and measurement errors make data analysis for UGW-based SHM applications complex. Analytical solutions are available only for specific cases, and simulations can be computationally expensive.

3.3.1. Damage Detection and Localization with UGW

Damage Detection (SHM Level 1): For basic damage detection, statistical damage metrics are used to compare signals from the pristine structure with those from the structure in its damaged state. When damage occurs, the new wave packets generated by the PWAS transducers will scatter differently, allowing for the detection of changes in the signal【17】.

Damage Localization (SHM Level 2): Damage localization is typically achieved using triangulation, where the Time of Flight (ToF) of wave packets scattered by the damage is measured. The intersection of ellipses drawn around each actuator-sensor pair provides the most probable location of the damage. For example, in an experiment on damage location using three PWAS transducers on an aluminum plate with movable artificial damages, the ToF of wave packets is used to calculate the damage's location through statistical fusion of the damage indicators. This method provides a reliable way to determine the damage location with high accuracy.



IV. MULTI MODAL SENSOR APPROACH TO SHM OF METAL AND COMPOSITE STRUCTURES

A comprehensive and dependable SHM approach for damage assessment up to Level 4, suitable for both metal and composite structures, and addressing their various damage types, is difficult to achieve with a singlet SHM method. This challenge arises because each SHM method has different sensitivities to structural properties, as well as varying degrees of susceptibility to environmental influences (see Table 1, Table 2, and Table 3). A multi-sensor approach can significantly enhance the comprehensiveness, accuracy, and reliability of the damage assessment. To establish such a system, two steps are required: first, selecting the appropriate SHM methods and their corresponding sensor network; and second, defining an effective data evaluation process for accurate damage inspection.

4.1. Selection of SHM Methods and Sensors

The choice of SHM methods directly relates to the measurement entities required and the types of sensors needed. Key considerations for designing a sensor network include:

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a. Optimal sensor placement: Proper locations for excitation and measurement are essential.
b. Robustness: The reliability of the measurement signal and sensor equipment is crucial.
c. Structural constraints: Factors such as volume, weight, and curved surfaces affect sensor placement.
d. Environmental factors: Sensors must withstand conditions such as dirt, moisture, and high temperatures.
e. Cost constraints: Budget limitations must also be considered when selecting sensors and measurement equipment.

Designing the sensor network is a complex engineering task, which is outside the scope of this article. However, the qualitative analysis of SHM methods and their sensors is provided, based on their theoretical capabilities (e.g., ability to assess specific damages or achieve different SHM levels). For instance, complete damage identification is possible only through active dynamic techniques, such as the Ultrasonic Guided Wave (UGW) method. Dynamic SHM methods are highly sensitive to many structural properties and changes. However, they are also more prone to environmental influences. Additionally, higher-level damage features are challenging to back-calculate, especially with noisy data and unknown environmental conditions. To address this, it is crucial to incorporate measurement entities that are more closely aligned with specific structural changes. Static strain-based methods, such as the Zero-Strain Trajectory (ZST) method, can help in this regard. These methods are not influenced by mass or damping properties, and many types of damage can directly affect the measured surface strains (see Table 1). Fiber Optical Sensors (FOS) are particularly advantageous because of their high technological readiness and ability to measure strain along a defined curve or across large areas using a sensor grid. This allows for reliable conclusions on the location and size of damage. Furthermore, less reliable methods can complement the assessment or reduce the sensor grid density.

Another method is Electrical Impedance Tomography (EIT), which leverages the electrical properties of conductive structures, such as Carbon Fiber Reinforced Polymers (CFRP). EIT can monitor the location and size of damage across the entire structure but is also sensitive to environmental influences. While it requires costly evaluation equipment and robust electrode attachment, when combined with other SHM methods, EIT-based damage assessment can provide valuable insights.

A key advantage of a multi-sensor SHM approach is its ability to mitigate the impact of environmental influences. This can be achieved through additional sensors (e.g., for temperature or moisture), by back-calculating temperature from strain data under unloaded conditions, or by ensuring that the unloaded condition is maintained for dynamic evaluations. Moreover, self-diagnosis can be integrated into the system, allowing for the identification of faulty sensors. For instance, Electromagnetic Impedance (EMI) measurements can be used to diagnose Piezoelectric Wafer Active Sensors (PWAS) used in the UGW method.

For detecting delaminating initiation in CFRP or GFRP components, combining the UGW and EMI methods could prove effective:

a. UGW Method: For far-field sensing and SHM Level 4 assessment, leveraging both linear and nonlinear scattering effects.
b. EMI method: For self-diagnosis and local SHM Level 3 assessment through linear and nonlinear effects.

4.2. Definition of Data Interpretation Procedure

The Data Interpretation process in a multi-sensor SHM approach must account for the strengths and weaknesses of each SHM method to combine the data most effectively. This requires statistical data on the reliability of each SHM method and its damage assessment features. To maintain accurate final damage assessments, a component knowledge database should be regularly updated throughout operation and integrated with a centralized database that contains data from similar components in operation. The data evaluation process, illustrated in Figure 12, consists of four main steps:

1. Sensor Network: Collection of raw data from the various sensors in the network.
2. Raw Information Fusion: Combining sensor data from multiple sources to create a more accurate damage assessment.
3. Feature Extraction: Identifying key features from the combined data that are indicative of damage.
4. Decision Making and Fusion: Evaluating the extracted features to make conclusions about the potential structural damage. If damage is detected, it might trigger manual inspection, and the knowledge database is updated with the new findings.

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This comprehensive evaluation procedure helps integrate multiple SHM methods and sensors for more reliable and accurate damage assessment.

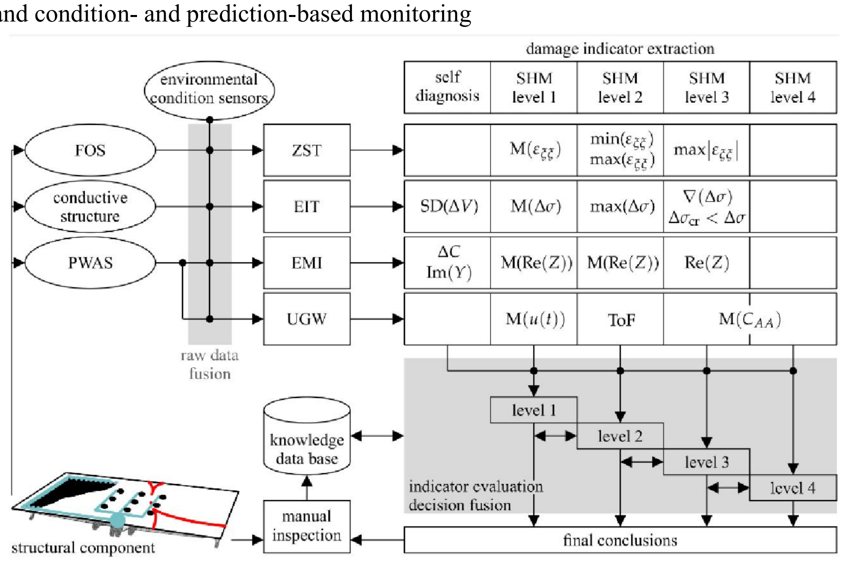
The design of the sensor network for a multi-sensor SHM approach is primarily influenced by the data requirements of the selected SHM methods. This process must be adapted to the structure of interest, taking into account its geometrical and environmental constraints. Additionally, sensors for monitoring environmental conditions (such as temperature and moisture) may be necessary. A multi-sensor network utilizing Piezoelectric Wafer Active Sensors (PWAS), Fiber Optical Sensors (FOS), conductivity sensors, and temperature sensors, combined with SHM methods like the ZST approach, direct or thin-film-based Electrical Impedance Tomography (EIT), Electromagnetic Impedance (EMI), and Ultrasonic Guided Waves (UGW), can effectively assess key damage types in both metal and composite structures.

However, raw measurement data from these sensors must be associated and fused—either through model-based or data-based methods—to account for environmental factors like thermal state . For example, model-based fusion of temperature and strain data can help compensate for temperature effects in the neutral axis damage assessment feature of composite beams.

A range of damage indicators and features can be extracted for self-diagnosis of the sensors and for all four SHM levels of damage assessment, as outlined in Section 3. These indicators are then evaluated using a knowledge database, which could contain values such as threshold data or UGW scattering patterns, and be based on either models or data. The results from various evaluations are combined at different SHM levels, using methods such as weighted decision-making. Careful weighting is essential and requires knowledge of the sensor network's condition (via self-diagnosis) as well as statistical data on the reliability of each SHM result. While studies have addressed the statistical reliability of SHM methods, generalizing these findings remains challenging. However, statistical data should ideally include the reliability of conclusions, such as the probability that the predicted damage location is accurate (e.g., as shown in Figure 6b)

Damage assessment proceeds stepwise, starting with detecting potential damage. If damage is detected, the process continues with conclusions about localization, size, and type of damage. For instance, determining the size and type of damage using UGW scattering patterns requires prior knowledge of the damage location, i.e., understanding from which direction the scattered wave is traveling (Figure 8b). However, this is not always a straightforward process. Lower-level conclusions can be revisited or corrected if higher-level assessments do not align with the initial findings.

Finally, the structure's overall health state is determined at SHM Level 5, which may prompt manual inspection and repair. In today's aircraft design, even the mere existence of damage may require immediate repair according to regulatory standards. Looking ahead, strategies involving a knowledge database or digital twin could enhance the evaluation of current structural integrity or predict future damage, optimizing repair decisions based on regulation, safety standards, and condition- and prediction-based monitoring



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V. CONCLUSION

It relying solely on individual state-of-the-art SHM methods may not provide a comprehensive damage assessment for full-scale structural components. The combined use of dynamic SHM methods, such as PWAS-based techniques like EMI and UGW, offers significant potential for damage identification due to their sensitivity to various structural features. However, these methods are affected by structural and environmental uncertainties. In contrast, static SHM methods, like Fiber Optical Sensors (FOS), are technologically advanced and provide straightforward back-calculation of damage from damage indicators. As a result, uncertainties in static methods can be more easily identified or compensated for by additional sensor data.

The fundamental physical effects used in static and dynamic SHM methods differ significantly, which can lead to more reliable damage assessment when combined. This redundancy improves the overall reliability of the system. Therefore, a reliable multi-sensor SHM approach should integrate both static and dynamic methods for damage assessment. The Information Fusion process for multi-sensor SHM needs to be tailored to meet the specific requirements of each method. While some SHM methods already incorporate Information Fusion in their feature extraction and damage evaluation, optimizing the fusion of data to achieve reliable damage assessments remains an ongoing area of research

A clear, structured data evaluation procedure is proposed for effectively combining multiple SHM methods in a multi-sensor approach, enhancing the reliability of the overall damage assessment. However, successful decision-level Information Fusion will require the development of generalized and verified statistical data, an area that warrants further research. Looking forward, future multi-sensor SHM systems should incorporate structural analysis data to expand damage assessments to a full structural integrity evaluation (SHM Level 5), offering a more complete and accurate picture of the structure's health.

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