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PROBABILITY OF DETECTION: A RELIABILITY ASSESSMENT APPROACH FOR STRUCTURAL HEALTH MONITORING SYSTEMS IN CIVIL ENGINEERING

DR. DANIEL KANZLER[*], DR. VAMSI KRISHNA RENTALA[*], YOGI JAELANI[†] AND PROF. DR. SYLVIA KESSLER[†]

[*] Applied Validation of NDT (AV-NDT),
Berlin, Germany

[†] Helmut Schmidt University/University of the Federal Armed Forces Hamburg
Chair of Engineering Materials and Building Preservation
Hamburg Germany

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Abstract. Transitioning from periodic maintenance to condition-based maintenance in safety-critical sectors hinges on the effective application of Structural Health Monitoring (SHM) methods. While SHM techniques have seen widespread implementation across various industrial domains, unlocking their full potential necessitates a deep comprehension of its reliability.

In the realm of Non-Destructive Testing (NDT), the estimation of reliability often relies on Probability of Detection (POD) models. However, transferring these models from NDT to SHM proves challenging due to the myriad of variables and the inherent complexity of the structures involved. Consequently, adopting POD methods, as used in NDT techniques, fails to yield accurate reliability assessments for SHM systems. This study endeavors to fill this gap by developing POD models tailored for SHM, specifically focusing on their applicability in vibration-based monitoring for civil engineering bridges.

This presentation serves as a comprehensive introduction to the field of reliability assessment within SHM, catering to both individuals interested in the subject and seasoned SHM experts.

1 THE VALUE OF CAPABILITY ASSESSMENTS

The question of "How much does it cost NOT to do quality inspections?" yields varying answers across industrial sectors, products, services, and required quality standards. Yet, a glance at sectors like aviation or energy reveals that the cost of forgoing quality inspections can potentially soar into billions of dollars [1],[2],[3]. Also, within civil engineering, a catastrophic event could lead to expenses amounting to one billion dollars [4]. It is evident that opting out of inspections is an ill-advised decision.

The query, "How often should I inspect to avoid a catastrophic failure?" poses a complex challenge. The field of risk management endeavours to find a sustainable solution by maximizing quality to ensure social safety (social sustainability), minimizing financial costs (economic sustainability), and conserving raw materials and supplies (ecological sustainability) [5]. In safety-critical sectors utilizing non-destructive testing (NDT) methods, determining testing intervals is a pivotal discussion in striking a balance among these goals. If the interval is too short or frequent, money is expended without commensurate benefits. Conversely, if the interval is too long, the risk of a catastrophic event looms large. Both scenarios—wasteful spending on inspections and catastrophic events resulting from insufficient inspections—are undesirable. Hence, finding a suitable equilibrium among these sustainability facets is of utmost importance.

In the domain of NDT, the discourse has historically centred on technical aspects concerning materials, potential defect behaviour, and applied loads. Concerns about statistical uncertainties were typically addressed through safety factors. An illustrative example is the safe-life concept in aviation, where aircraft were retired after a third of their estimated lifetime, incurring exceptionally high and ecologically unsustainable costs. However, one critical factor often overlooked in an aircraft's lifetime was the testing system's capability. The adoption of the damage-tolerant concept, which factored in the testing system's evaluation, led to significant cost savings for the US Air Force [6].

In the context of continuously monitoring systems, evaluating the system's capability is pivotal in assessing potential costs, utilization, and the value of a monitoring system. The question, "What can a monitoring system detect?" remains unanswered despite fifty years of reliability evaluation in NDT.

2 RELIABILITY OF STRUCTURAL HEALTH MONITORING

When comparing a Non-Destructive Testing (NDT) system to a Structural Health Monitoring (SHM) system, several significant differences emerge, which in turn impact the evaluation of reliability. These disparities necessitate distinct definitions of reliability for each, owing to the varying aspects that are relevant:

Continuous Testing: SHM systems typically operate continuously, as opposed to periodic testing in NDT. This continuous nature introduces unique considerations in assessing reliability.

False Alarm Rate: SHM systems face challenges related to false alarms, which are less common in NDT. Determining reliability must account for the system's ability to minimize false alarms while identifying genuine issues.

Localization and Characterization Challenges: SHM often deals with complex structures, making the precise localization and characterization of defects more challenging compared to the relatively simpler targets of NDT.

Moreover, the factors influencing reliability in SHM differ significantly from those in NDT applications:

Different Role of Humans: In NDT, human operators play a pivotal role in conducting inspections. In contrast, SHM systems operate autonomously or with minimal human intervention, altering the reliability considerations.

Aspects of Calibration: Calibration requirements in SHM can differ from NDT due to the continuous and autonomous nature of SHM systems.

Environmental and Operational Conditions: SHM systems are exposed to various environmental conditions and operational contexts, which can impact their reliability differently than in controlled NDT environments.

While these are some of the major influencing parameters, it's important to note that there are additional factors not discussed in this article, such as sensor degradation, algorithms, and variations in structure and defect parameters.

Consequently, the evaluation of reliability for SHM systems demands the utilization of specific reliability models that account for these unique characteristics and challenges.

2.1 Aspects of Reliability

Continuous data acquisition is a prominent advantage of monitoring systems, often transitioning to quasi-continuous acquisition with small time intervals between data collection points relative to damage creation or propagation processes. This capability plays a crucial role in ensuring the safety and reliability of components, especially in high-stakes industries.

In the realm of Non-Destructive Evaluation (NDE), the primary concern is the safety of components in relation to their failure processes. In the early days of reliability evaluation, aviation was at the forefront. To grasp the evaluation process's objectives, it's instructive to delve into the details. Consider a typical failure scenario in aviation, such as a broken turbine blade or disk. Over the lifetime of these components, small cracks may develop, potentially compromising safety. NDE methods, employed at various time intervals, can detect cracks before they reach critical dimensions. Even if a crack goes undetected by NDE (an issue often discussed when establishing the a90/95 characteristic) [7], the combination of frequent testing intervals and crack propagation modeling contributes to a highly safe environment.

In contrast, when planning SHM, the aspect of inspection intervals becomes largely irrelevant. For SHM systems, the focus shifts to assessing the cost, reliability, and lifetime value of the system. Estimating costs, including both product and lifetime expenses, is relatively straightforward. The value of the SHM system, closely tied to product quality, hinges on its reliability, ensuring that the costs are invested sustainably.

Similar to NDE systems, the reliability of an SHM system can be defined by its ability to detect critical defects, differentiate between defect classes, localize issues, and minimize false alarms during the sensor's active lifetime [8]. However, the importance of SHM lies in detecting, characterizing, and localizing defects, whereas in NDE, the emphasis is on detectability over time.

The success of reliability assessments in NDT across safety-critical sectors stems from their ability to objectively estimate the true scenarios during component testing through scientifically grounded procedures. This approach incorporates relevant influencing factors, providing answers to questions about potential outcomes from component testing.

In SHM systems, the main costs typically stem from potential defect indications. Retesting is usually feasible, but if false alarms persist, the structure (potentially inaccessible) may require retesting through NDE, repair, or even demolition. In such cases, the consequences of false alarms are often more severe than in NDE.

Due to continuous monitoring, the time factor becomes less critical compared to NDT, shifting the focus toward localization and characterization of defects. However, accurately assessing localization and defect type solely based on SHM signals is challenging. For example, in ultrasonic echo-based monitoring, a similar signal could result from a small defect near the sensor or a large defect far away from it [9].

To address these challenges, additional information and knowledge are typically incorporated into the system. This may involve multiple sensors, regular NDE inspections, and an understanding of critical defect hotspots based on component geometry. The monitoring system becomes an integral part of the overall quality management process.

2.2 Influencing Parameters

Standards and guidelines for NDE are designed to minimize undesired influences and provide a framework for reliable testing methods. In Europe, these standards define specific corridors of relevant influences within which an NDE method can be effectively applied. Here are some key considerations:

1. Human Factors: ISO 9712 [10] addresses major influences related to human factors in NDE. This includes factors such as the experience, training, and physical fitness of personnel involved in the testing process.
2. Reference Parts: Shifts within a testing process are monitored by comparing test results to reference parts before and after a testing interval, as discussed in [11]. This helps ensure the stability and consistency of the testing method.
3. Equipment Quality: Quality standards, such as those specified in [12], are crucial for maintaining the quality of NDE equipment, particularly in the production corridor of ultrasonic testing probes.

However, the influences in Structural Health Monitoring (SHM) can differ significantly from NDE, requiring a distinct approach:

1. Human Involvement: While the role of humans is more pronounced in NDE, they also play essential roles in SHM. They are responsible for planning and executing the installation of sensors, preparing surfaces for sensor placement, and conducting quality control checks on sensor functionality. In data assessment, especially for new SHM systems, and when indications are detected, human decision-making is crucial for determining future actions, which may include manual verification through alternative testing methods like NDE. Evaluating human influences within the SHM approach is an evolving area of consideration for the community.
2. Sensor Functionality: In contrast to NDE, where sensors are often removable, SHM sensors are typically permanently attached to structures. Therefore, traditional pre- and post-monitoring evaluations, as well as testing sensitivity with reference defects near the sensors, may not be practical. Assessing sensor functionality in SHM systems may require alternative solutions.
3. Environmental Influences: The primary influences on SHM systems stem from their usage in real-world conditions. SHM systems excel in monitoring inaccessible areas that may be subject to temperature fluctuations and various weather conditions. These environmental factors can affect data collection and interpretation, making it essential to consider them in the overall reliability of SHM systems.

In summary, while NDE standards provide a well-established framework for addressing influences and ensuring reliability, SHM presents unique challenges due to its continuous and often permanent monitoring nature. Human factors, sensor functionality, and environmental conditions are key considerations in the realm of SHM, and developing standards and guidelines tailored to these specific challenges is an ongoing endeavour within the SHM community.

2.3 SHM Reliability Concepts

The Receiver Operating Characteristics (ROC), as shown in **Figure 1**, curve is a valuable tool for assessing the reliability of inspection systems, focusing on the trade-off between the false alarm rate (FAR) and the general probability of detection (POD). This method is well-established and widely used in various fields, including Non-Destructive Evaluation (NDE) [13]. However, ROC has a limitation—it does not account for the criticality of defects, which is a crucial factor in safety-critical contexts.

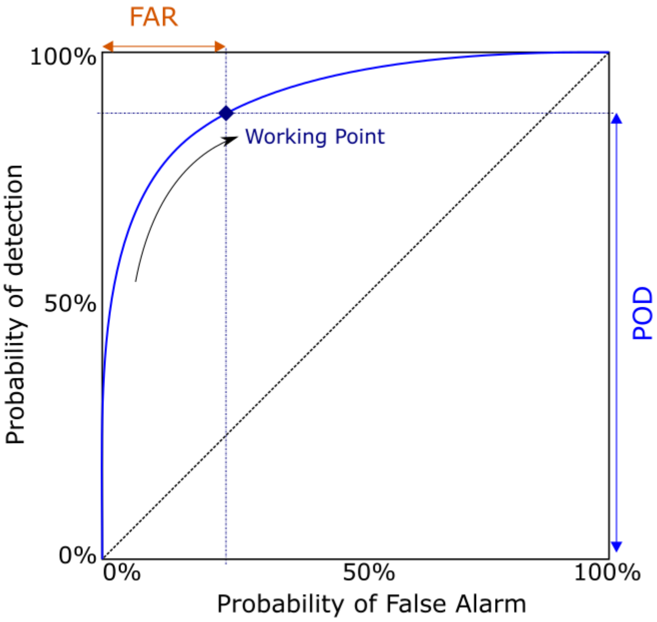

Figure 1: Receiver operating characteristics with a working point for an inspection system

In safety-relevant areas, determining the criticality of defects is essential when deciding whether a method is suitable for a specific damage scenario. This is where the Probability of Detection (POD) becomes an important tool, as illustrated in Figure 2. Statistical techniques, such as bootstrapping methods [14], are employed when there is a sufficient data pool. In NDE, parametric approaches based on specific statistical models, such as the hit-miss approach [15], are common. These methods typically require independent datasets and a minimum number of defects with specific parameters, often around 40 in the case of hit-miss analysis.

However, gathering a statistically significant amount of independent defect data can be challenging. Despite this limitation, the POD approach remains valuable because it describes the relationship between detectability and the interplay between the defect and the physical principles of the sensor.

In Structural Health Monitoring (SHM), the relationship between sensor response and defects is often characterized as a Damage Index (DI), and the definition of DI may vary depending on the specific testing situation.

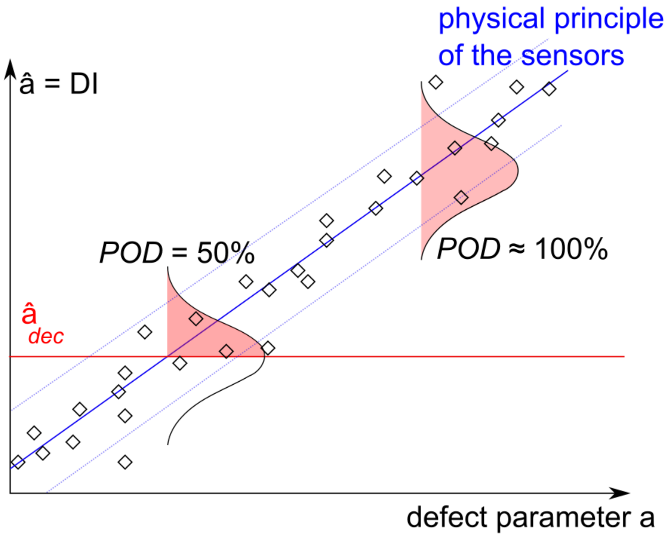

Figure 2: Physical relationship between the sensor response (DI) and a defect parameter

For SHM, a tailored approach involves combining available knowledge within a common framework, which can be interpreted as a form of POD:

Software Simulations: Software simulations are instrumental in understanding the physical principles of SHM methods, particularly regarding sensor output in the presence of defects. However, it is crucial to validate simulations for each specific application. Simulations can account for potential deviations due to influencing parameters, enabling the estimation of a preliminary distribution for later POD assessment. Nonetheless, there's a risk of neglecting real-world influences that may dominate the inspection process and are not considered in the simulations.

Statistical Dependency: Accepting the statistical dependency of data is a departure from traditional POD methodology and is exemplified in the "length at detection (LaD)" model [16]. This model was developed in the aviation industry to address the additional requirements for SHM assessments and acknowledges that data collected in SHM may not always meet the strict independence criteria common in traditional NDE applications.

In conclusion, while ROC remains a valuable tool, especially for FAR and POD assessments, addressing the unique challenges of SHM in safety-critical contexts requires a more nuanced approach. This involves considering criticality, employing software simulations, and acknowledging the statistical dependencies of the data, as exemplified by the LaD model.

2.4 SHM Concept for Civil Engineering

The DTEC project conducted by the Helmut-Schmidt-University University of Armed Forces in Germany serves as an exemplary assessment project in the field of Structural Health Monitoring (SHM). The project involves equipping several bridges with various sensors to establish a statistical methodology for reliability evaluation. The ultimate goal is to create a robust reliability assessment framework, despite challenges related to data dependency and the scarcity of defect data.

The project's initial steps include simplifying the reliability evaluation model and employing simulation software to gain insights into the relationship between sensor signals, potential loads, and defects. The simulation software used is a finite element-based model called openTU1402 [17], as shown in **Figure 3**, primarily used in an academic context.

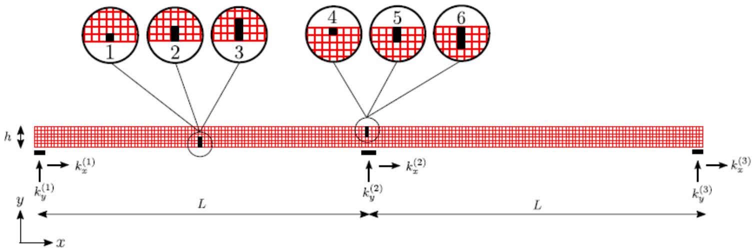

Figure 3: open GUI benchmark TU1402

A crucial concept within SHM is the Damage Index, which quantitatively measures the severity or extent of damage in a structure. This index is calculated based on sensor data, encompassing measurements related to strains, displacements, accelerations, temperature variations, and other relevant signals. The Damage Index aims to provide a numerical representation of the structural condition, helping differentiate between an undamaged state and a damaged state. It serves as a valuable indicator for decision-making, structural health monitoring, and assessing the SHM system's detection accuracy, often expressed as POD [18].

In the case of bridge safety, a critical parameter is the percentage reduction in stiffness of the Finite Element Model (FEM) structure or the bridge itself. By conducting these steps, the physical relationship between sensors and potential defects can be evaluated, as shown in.**Figure 4**.

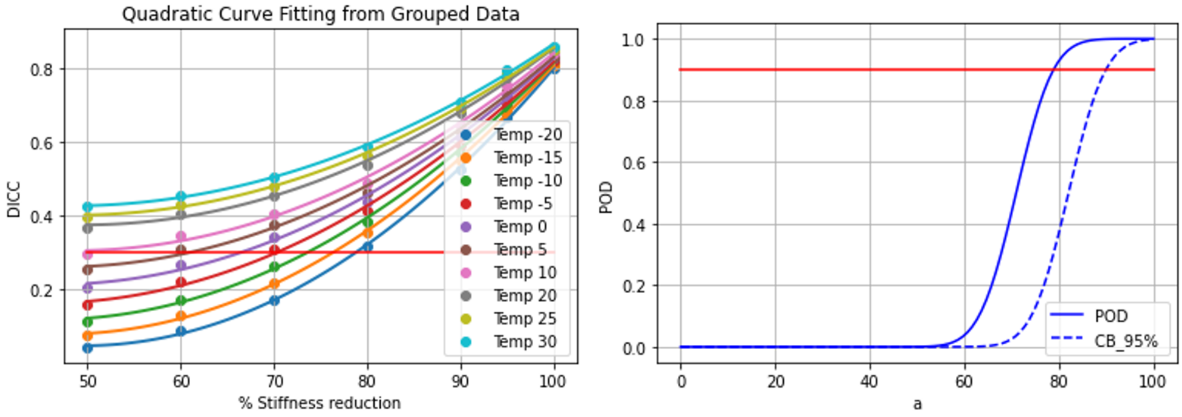

Figure 4: SHM-POD based on a LaD model used on simulation data origins out of TU1402

Considerations for potential influencing parameters, such as temperature variations, are important for SHM sensors exposed to weather conditions. In the assessment, temperature variability ranging from -20°C to +30°C was taken into account.

The "length at detection (LaD)" model for PODs was used to estimate a preliminary POD curve based on these assessments. This model acknowledges the statistical dependencies in the data and is suitable for handling SHM assessments, particularly when dealing with limited defect data in combination with simulated data.

For a detailed evaluation of the POD in the context of the DTEC project, you can refer to [19]. This comprehensive report includes a discussion of the results and a comparison with a typical Non-Destructive Evaluation (NDE) approach. The article you're reading focuses on outlining the procedural steps for evaluating the reliability of an SHM system in civil engineering contexts.

3 LESSON LEARNED AND OUTLOOK

This article underscores the distinctive nature of reliability assessment for Structural Health Monitoring (SHM) systems, particularly in civil engineering (CE), compared to Probability of Detection (POD) evaluations in Non-Destructive Evaluation (NDE). The unique requirements of SHM necessitate alternative data acquisition approaches, such as utilizing simulation software to calculate POD, often through methods like the "length at detection (LaD)" model.

However, it's important to note that an essential step in the process is still pending: the validation of simulation results using real data from bridges, accounting for the fluctuations and variations present in actual bridge conditions. This validation aspect remains a focal point of the ongoing DTEC project.

The key takeaways from this article are as follows:

Different Assessment for SHM: Reliability assessment for SHM systems cannot be approached in the same way as NDE due to their unique requirements and continuous monitoring nature.

Role of Simulations: Simulations hold a more prominent role in SHM compared to NDE, aiding in understanding and assessing the relationship between sensors, loads, and defects.

Advanced Mathematical Approaches: SHM relies on more advanced mathematical approaches, exemplified by the LaD model, to estimate POD and address the statistical dependencies present in the data.

For further information and deeper insights into the field of SHM, the provided references can be a valuable resource, and the authors are available to offer additional expertise and knowledge on the topic.

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