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Consideration of simple approaches for structural health monitoring of structures in developing countries - An overview

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ABSTRACT. *Structural health monitoring (SHM) is an advanced tool that revolutionizes the capability of a structure to act as a responsive system – detecting changes and responding with performance analysis. But, for developing countries, its need is undermined due to its costly deployment. However, contrary to the costly belief, its use is direly needed in densely populated developing countries. Therefore, a simple and cheaper technique (despite lesser precision and accuracy) can help in the early detection of damages in structures. Unfortunately, SHM implementation has been inadequate in developing countries, consequently, limited literature is available to assess. Therefore, the main goal of this literature review is to identify and analyze various SHM approaches and then propose a simple yet effective approach for achieving the basic amenities of SHM. By analyzing previous highly reputable journals, it was deduced that vibration-based approaches are the most cost-effective and simplistic to implement, which have resurged recently due to the increased use of computational tools that minimize extraneous data and provide efficient noise removal. The use of combination techniques in SHM can be cost-effective and accessible for developing nations, providing solutions for infrastructure sustainability.*

Keywords: vibration-based method, structural health monitoring, damages, simple approach.

1. INTRODUCTION

Structural health monitoring is a process of increasing the serviceability of a structure – performance, and sustainability. It is done through the deployment of sensors in key change-dominant areas, thereby the responses generated are recorded by an automated monitoring system [1]. The maintenance profile that it envisions makes it a somewhat cost-effective and safe solution in the long run. An approach of SHM is based on various components that act intertwined; a sensing network, a data processing system, and a response system based on damage pattern evaluation. The development of low-cost systems for accurate measurements of SHM data is in full swing, due to the rise of electronic integrations – highlighting the need for SHM in today's world [2]. Integrating SHM with lifecycle management is crucial to accurately assess and predict structural behavior, optimize operation and maintenance, and extend the design life of engineering structures.

SHM can be divided into two categories: global and local. These two strategies offer distinct types of information and serve different analysis purposes. The global approach provides a comprehensive view of the structure's overall health, while local monitoring focuses on specific components and their performance. Both strategies can further be classified into data-driven and physics-based approaches. Data-driven approaches use pattern recognition tools to sense, locate, and interpret damage based on the structure's health. Physics-based methods, on the other hand, use a calibrated numerical model and FE model updating to predict damage based on measured data [3]. Both global and local structural health monitoring strategies are essential for evaluating the condition of large civil structures. The selected strategy should be in line with the desired outcomes and objectives of the analysis. The SHM system should also integrate well with other existing systems and be regularly calibrated and validated to ensure its accuracy and reliability.

Modal analysis is a vibration-based dynamic SHM approach that incorporates modal parameters, primarily physical and material-based properties such as vibration frequencies, damping ratios, and mode shapes. This input-output method is based upon excitations (inputs) by hammers or shakers and structural responses (outputs) recorded by sensors to measure modal parameters [4]. The vibration-based method, also known as a modal analysis approach, is used to determine modal parameters in structures. This technique falls within the domain of frequency-based damage detection, which is a simple method for detecting damage based on changes in a structure's natural frequencies. These changes can be caused by alterations in the structure's mass, stiffness, or other properties. The vibration-based method is effective in detecting such changes and can be used to assess structural damage.

To the best of the authors' knowledge, the suggestion of the VBM approach has not been highlighted before for developing countries. Therefore, this review paper aims to provide a basic idea of SHM and its potential benefits for developing countries, it further tries to converge towards the combined use of the VBM method and computational models like machine learning and other numerical methods; which prove cost-effective in the long use. SHM is slowly becoming a need in developed countries, owing to its maintenance, inspection, site condition assessment, and sustainable benefits. Hence, various approaches are being developed according to the need. Their use will only increase over time making structures safer and more sustainable.

2. IMPORTANCE OF SHM

The implementation of SHM technologies has numerous benefits that improve the design and management of structures. Through SHM the proper maintenance and management of large infrastructures lead to their continued service and economic operation [5]. Nielsen et al. [6] proposed that probabilistic models for inspections and deterioration processes of in-use structures such as wind turbines can be done through risk-based approaches that benefit the maintenance cost-based optimizations. Baas et al. [7] presented that the performance and critical behavior against site-specific conditions such as hygrothermal, static, and dynamic behavior of newly applied design methods of structural systems can be assessed and standardized using SHM. Wang et al. [8] proposed that recording SHM data in extremely disastrous events of large structures can be utilized to investigate and establish references for serviceability and real-time safety assessments.

Among other potential benefits, the first and most obvious benefit is increased human safety. Even at the lowest level of SHM implementation, the early strength degradation of a structure can be highly beneficial to provide early warning for safety issues [9]. Zhang et al. [10] found that intelligent monitoring technologies of SHM by the use of different sensors such as acoustic emission technology for non-destructive testing of cable bridges lead to more accurate data estimation which can be optimally used to schedule maintenance and repair activities. Kamariotis et al. [11] applied the value quantification framework of the vibration-based SHM method on a realistic numerical model subjected to gradual and shock deterioration that resulted in a prior decision support tool to indicate the use of SHM for a structure. Hence, various approaches are being developed according to the need. This, in turn, would be of economic and environmental benefit.

3. ADVANCED AND SIMPLE APPROACHES FOR SHM WITH THEIR BASIC PRINCIPLES

The advanced and simple approaches then in-depth have numerous techniques for identification and assessments. Structural damage assessment based on vibration data has shown great promise [12], the modal-based assessment methods are required to form a baseline from the previously undamaged structure which can be updated and validated by alternate correlation studies to provide comparisons of applied methods [13]. It is worth noting that while these methods may be considered advanced or simple, they may not always be the most appropriate or effective solution for a given problem, and a simpler method may be more suitable in many cases. The choice of technique should be based on a thorough evaluation of the specific requirements of the problem and the available data. The approaches are based on the type of damage identification spaces and their functionality as given in Table 1 are; heuristic, modal, numerical, and geometric.

Table -1: SHM approaches based on their identification spaces and functionality

Approach Functionality	Approach type based on Identification Space			
	Heuristic	**Modal**	**Geometric**	**Numerical**
Simple	Seismic risk assessment [14], rule-based [15]	Vibration-based method [16], ambient vibration [17]	Acoustic emission [18], strain gauge [19]	Model-based (finite element methods) [3], machine learning [20]
Advanced	Meta-heuristic algorithms [21], swarm optimization [22]	Strain modal analysis [4], modal flexibility and clustering methods [23]	Data fusion techniques [24], digital image correlation [25]	Bayesian networks, and Artificial Neural Networks (ANNs) [26]

For the modal type of monitoring, accelerometers are suitable instruments to measure the dynamic response of the structure to vibrations, either forced or natural. By applying the baseline correction technique, the accelerometers can be made multifunctional [27]. The modal parameters can be used in model updating for finite element techniques [20], or through the application of machine and deep learning algorithms, mathematical correlation can be easily made, they also have proven effective in removing noise. Additionally, deployment does not require heavy machinery and can be obtained in regular conditions using modern sensing systems attached to the structure [28]. This makes the technique simplest to implement for any structure size, making them a popular damage detection method [29]. Therefore, this makes the vibration-based methods the simplest of all that have multi-combinational options in all situations.

4. ADOPTION OF A SIMPLE APPROACH FOR SHM IN DEVELOPING COUNTRIES

For populous developing countries, SHM deployment is a non-issue, as the main amenities of life are more important than the integrity of a structure. However, Annamdas et al. [30] found that the development of cost-effective SHM approaches has been a desirable area of research in the Asian region. According to the literature review, it has been perceived that the simplest approach which can highlight strength degradation at using minimal cost is the vibration-based method (VBM) which utilizes the modal parameters – time, frequency, accelerations, damping ratio, etc. VBM is traditionally applied on buildings where seismicity and in-service performance needs to be analyzed. It is most successful when implemented with clear deliverables and system specifications. And, for large case study buildings, it has been quite successful in its role [31]. It is not necessary to have prior knowledge of the damage's location or to have sensors near the damage, as the modal parameters are a characteristic of the entire structure.

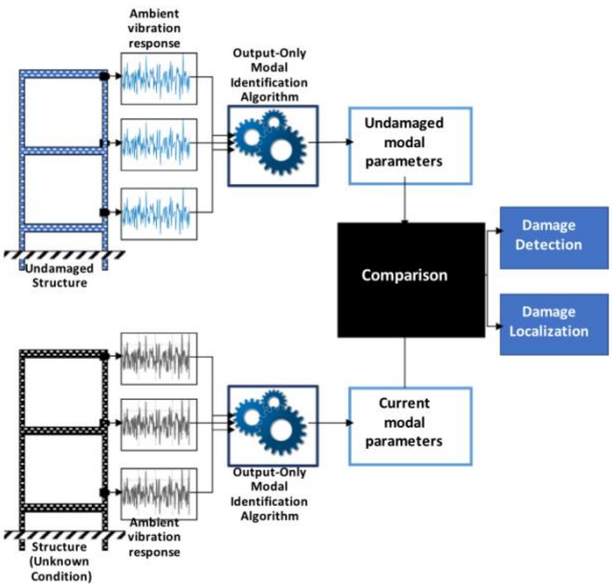

Fig -1: A schematic of output-only parametric vibration-based damage detection methods [32]

The combination of different techniques in SHM is done to increase the accuracy and reliability of damage detection. Figure 1 highlights the combined use of algorithms and the VBM approach, which are cost-effective in long run and can achieve overall good results for developing countries. Recent studies have shown that with deep learning algorithms, VBM raw data acceleration time histories can be assessed much faster for damage and locality with post-processing and hand-crafted extractions [32]. This approach leverages the strengths of each method and overcomes individual limitations. For example, combining vibration-based techniques and machine learning algorithms results in more sophisticated damage detection algorithms. Implementing this combination does not require new hardware, as both vibration sensors and machine learning algorithms can be easily implemented using existing technology. The combination is straightforward and cost-effective, as it does not require a large amount of data or complex signal processing algorithms. The goal of combining techniques in SHM is to provide more accurate and reliable damage detection, while also making SHM systems simpler and more accessible.

5. CONCLUSION

This review paper explores the prolific potentials of SHM and then necessitates the need for SHM's VBM approach from reputable published literature. The following conclusions have been made from the literature review:

- SHM systems can help detect and assess damage promptly, improving the safety of infrastructure, especially in developing nations where resources for frequent inspections are limited.
- So far, the deployment of SHM in developing countries has been meager with primary reasons of cost. The implementation of SHM systems using the amalgamation of different techniques can be cost-effective, especially for developing nations where budgets for infrastructure maintenance are often limited.
- The combination of techniques can be easily implemented without the need for new hardware, making it accessible to developing nations with limited resources and technical expertise.

In a nutshell, combination of techniques in SHM can be efficient and beneficial for developing nations, providing cost-effective and accessible solutions for infrastructure maintenance, safety, and sustainability.

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