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Review

The use of intelligent computational tools for damage detection and identification with an emphasis on composites – A review

Guilherme Ferreira Gomes*, Yohan Alí Diaz Mendéz, Patrícia da Silva Lopes Alexandrino, Sebastião Simões da Cunha Jr, Antonio Carlos Ancelotti Jr

Mechanical Engineering Institute, Federal University of Itajubá, Brazil

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A B S T R A C T

Today, the Structural Health Monitorin (SHM) methodology is the main way to deal with the detection and identification of damages in a range of engineering sectors, mainly in the military and civil aerospace industry. The need to monitor damages and failures in increasingly complex structures has led to the development of various detection techniques. Identification of damages through intelligent signal processing and optimization algorithms are particularly emphasized. The methods discussed here are mainly elaborated by the evaluation of modal data due to the great potential of their application. Moreover, the optimization of damage identification is approached through methods of optimal positioning of sensors for the acquisition of the data that must be evaluated so that conclusions can be made. This article discusses the use of computational and intelligent techniques for structural monitoring in the form of a review with emphasis on composite materials. Despite the excellent mechanical performance already known about composite materials, they have a weak point. While damages, in a metallic material are easily visible (in some cases), composite materials often have the superficial appearance as if in perfect condition, when, inside, there are serious damages. This paper can be seen as a guideline or a starting point for developing and improving SHM systems. The contents of this paper aim to help engineers and researchers find a starting point in developing a better solution to their specific structural monitoring problems, either by inverse methods, pattern recognition, and intelligent signal processing.

1. Introduction

Structural health monitoring is based on the use of reliable and robust indicators that allow the detection, location, quantification and, if possible, prediction of damages in mechanical structures. The studies related to the detection of damages in engineering structures are of notable interest, since the detection of a structural modification is of fundamental importance to avoid the occurrence of serious social, economic and environmental consequences. In recent years, several studies have been carried out aiming to develop several indicators based on the characteristics of static and dynamic responses of mechanical structures. Damage can be considered a change in the geometric or physical properties of a material. A structure with the presence of damage will have a mechanical behavior (parameter) different than a sound structure. These parameters are directly affected by the variation of the physical properties of the structure, such as its mass and especially its rigidity. In general, structural damage causes a local reduction of the rigidity of the structure and, as a consequence, modifies its characteristics.

Most damage indicators are based on time domain or frequency analysis to extract information through the modal characteristics or evolved indicators constructed from these characteristics. These indicators have proved to be efficient, but there are still areas that need to be improved. Many indicators present sensitivity problems, need a reference state and do not present the probability of detecting false alarms, reducing their reliability.

Nowadays, mainly due to the development of new materials, composite materials have been replacing traditional materials due to their high structural performance. With this, new damage detection strategies must be taken into account and further evolved. For example, while damage to steel armor is easily visible (mostly), composite materials often have the surface appearance as if they were in perfect conditions, when, in its interior, there are serious damages.

Composite materials have been widely used over the years in the aerospace industry and in other engineering applications where structural weight is one of the main justifications for their use. This is due to its excellent advantages such as: high strength and remarkable stiffness in relation to its specific mass, besides its high capacity to withstand

* Corresponding author.
E-mail address: guilhermefergom@unifei.edu.br (G.F. Gomes).

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(a) Inspection of wind turbines. (b) Inspection of aeronautical fuselages. (c) Bridge monitoring.

Fig. 1. An overview of the potential fields of application of structural monitoring techniques (retired from [72]).

fatigue and corrosion [52].

However, such composite structures, in service, may exhibit certain failure mechanisms, such as matrix cracking, fiber rupture and delamination. These failures are caused due to static overload, impact, fatigue, design errors and overheating. Essentially, delamination is considered the greatest "weakness" of laminated composite materials, leading to loss of structural integrity. Delamination can easily spread throughout the laminate of a composite structure and can lead to catastrophic failure when undetected [13].

Programmed visual inspections are usually time-consuming, expensive and require components to be readily accessible, as shown in Fig. 1. Other conventional methods (ultrasonic methods, thermography, X-rays and others) for prior detection of composite damage are often costly and depend heavily on the operator's skill and experience. Structural Health Monitoring (SHM) technologies offer a promising alternative and involve continuous monitoring of a structure using a non-destructive testing approach (NDT) using integrated sensors [43]. In addition, acoustic emission can also be seen as a SHM technique, because it is based on integrated acoustic sensors. But, nevertheless, it depends heavily on the operator's skills and experiences.

SHM inspections that explore vibration metrics are methods based on the principle that degradation due to damage to a structure changes vibration parameters such as natural frequencies, vibration modes and structural damping. Therefore, it is possible to analyze the measured vibration parameters to characterize and identify the presence of damage using inverse modeling techniques and computational intelligence.

According to [38], the SHM methodology aims to provide the tools for the constant or periodic monitoring of critical structural assets in order to determine the need for corrective actions and to prevent catastrophic failures. The SHM methodology therefore has potential application in many areas of engineering, including aerospace, mechanics and civil engineering. The basic idea of an SHM system is to provide a structure of interest, detection and analysis capabilities, and allow monitoring and evaluation to be performed periodically or continuously, autonomously. The SHM method offers potentially greater security, since failures do not evolve to an alarming level. As the potential benefits of this incorporation of SHM are enormous, a great deal of research is underway around the world to develop and improve systems that bring some degree of "self-awareness" to man-made structures [38].

The benefits of a system employing the SHM methodology include (but are not limited to) [38]:

- Allow optimum utilization of the structure, minimized downtime and avoid catastrophic failure;
- Give the designers an improvement in their products;
- Drastically change the work organization of maintenance services. That is, replacement of scheduled and periodic maintenance inspection by maintenance based on performance (or condition), reducing the current maintenance work.

In summary, the development of composite structural monitoring technologies aims to provide safety and cost savings (mainly in regard to maintenance). However, the number of practical applications of these technologies is still limited. This is mainly due to the complexity of possible damage scenarios and the high performance requirements of the identification methods employed. The study developed in this work refers mainly to the relationship between these two aspects, in order to reach a specific level of maturity. Detailed information on the concepts employed for this to occur will be presented in the following sections. The knowledge contained in these sections is necessary to fully understand the theme studied herein. The results obtained in this research clearly indicate the remarkable ability of intelligent computational methods to identify damages. The algorithms in their inverse formulations are capable of predicting delamination parameters.

This work aims to conduct a study on the main methods and methodologies used in the area of SHM for the detection and identification of damages in mechanical structures. The main propose of the article is based on the use of inverse methods for the detection of damages; for this, modal metrics and algorithms are discussed. The in-depth review work carried out in this study serves as a starting point for researchers and engineers in the SHM area who wish to develop or evolve a monitoring system that is capable of achieving an adequate level of confidence.

Although many studies have been reported on the structural health monitoring and damage detection, very few have been focused on the applied computational techniques for damage identification. To the authors' best knowledge, there are no (or very scarce) studies in the literature investigating the review of optimization methods for inverse problems of damage identification in mechanical structures. Details on heuristic optimization methods, as well as the formulation of inverse problems and construction of objective functions that significantly impact the problem, are presented. Here is the main contribution of this pioneering work.

This manuscript is organized as follows: in Section 2, a general bibliographic review is presented, addressing the techniques used in the study, mainly about mechanical vibrations and inverse methods.