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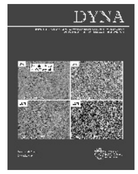

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Frequency-based methods for the detection of damage in structures: A chronological review

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Abstract
Infrastructure development is a common feature of emerging countries. As a result, the design and construction of complex structures susceptible to damage is becoming increasingly common. Over the years, multiple advances in Structural Health Monitoring (SHM) have allowed researchers and engineers to detect, locate, and quantify structural damage in critical components of civil engineering structures. Frequency-based methods have demonstrated their reliability in multiple numerical and experimental applications. This study presents a brief chronological literature review of methodologies based on frequency analysis that have been used in the detection of structural damage over the last forty years. It is worth noting that the paper focuses on computer-aided techniques such as artificial neuronal networks (ANN), genetic algorithms (GAs), and metaheuristics that have been employed to solve the inverse damage detection problem.

Keywords: structural health monitoring; frequency-based methods; optimization techniques; chronological review.

Métodos basados en frecuencia para la detección de daños en estructuras: una revisión cronológica

Resumen
El desarrollo en infraestructura es una característica común de los países emergentes. Como resultado, el diseño y construcción de estructuras complejas susceptibles a daños es cada día más común. A lo largo de los años, múltiples avances en Monitoreo de Salud Estructural (MSE) han permitido a investigadores e ingenieros la detección, localización y cuantificación de daños estructurales en componentes críticos de estructuras de ingeniería civil. Los métodos basados en frecuencia han demostrado su confiabilidad en múltiples aplicaciones numéricas y experimentales. Este estudio presenta una breve revisión bibliográfica de las metodologías basadas en el análisis de frecuencias utilizadas para la detección de daños estructurales en los últimos cuarenta años organizadas cronológicamente. Vale la pena señalar que este artículo se centra en resumir las técnicas asistidas por computadora, como las redes neuronales artificiales (ANN), algoritmos genéticos (GA) y las metaheurísticas que se han empleado para resolver el problema de detección inversa de daños.

Palabras clave: monitoreo de salud estructural; métodos basados en frecuencia; técnicas de optimización; revisión cronológica.

1. Introduction

Structural Health Monitoring (SHM) allows researchers to detect, locate, quantify, and predict structural damage in a wide range of civil and mechanical structural systems. It is clear that the application of such methodologies may contribute to reducing disasters, as well as increase the safety and quality of life of potential casualties of damaged structures.

In the SHM field, damage to structural elements may be associated with changes in the physical or mechanical properties of materials, with the consequence that their mechanical behavior differs from that of the undamaged structure. Natural frequency-based methods are probably the most studied approaches used to detect damage. The idea behind natural frequency-based methods is to identify disturbances in the natural frequencies of a structure, as these changes indicate alterations in physical properties, which

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may in turn affect the structural reliability of a system.

The great advantage of using frequency-based models is that natural frequencies are relatively simple to measure and the methods are easy to implement in practice [1]. There are, however, at least two limitations to using frequency changes to detect damage. First, significant damage may cause very small changes in natural frequencies, particularly for larger structures, and these changes may go undetected due to measurement or processing errors. Second, variations in the mass of the structure in question or measurement temperatures may introduce uncertainties in the frequency changes measured [2].

This paper presents a detailed chronological literature review of the frequency-based methodologies that have been employed over the last forty years to detect structural damage. Furthermore, special attention is paid to the different computational techniques used, such as artificial neuronal networks (ANNs), genetic algorithms (GAs), and metaheuristics that have been used to approach the damage detection problem.

2. Literature review

2.1 Preliminary studies

In the late 1970s, Cawley and Adams [3] proposed a methodology to detect, locate, and quantify structural damage, using a combination of measurements of the natural frequencies and a finite-element analysis. This research involved experimental tests performed on an aluminum plate and a cross-ply carbon-fibre-reinforced plastic plate, which showed similar results for the predicted and actual damage sites and for their magnitude. Further interesting work was presented by Gudmundson [4], who proposed a first-order perturbation method to predict the changes in resonance frequencies of a structure resulting from cracks, notches, or other geometrical changes. This method was tested both numerically and experimentally by examining three different examples: the determination of the effects of edge-cracks on the natural frequencies of a cantilever beam, the effect of a crack on the longitudinal eigenfrequencies of a bar and calculations for longitudinal vibrations of a bar with a circular hole at two different positions. Modeling the effects on eigenfrequency of cracks in a structure can be useful for predicting crack propagation, detecting crack growth and providing information about the size of defects.

Subsequently, Springer et al. [5] proposed a method based on the structural frequency-response function (FRF) and the shifts in the natural frequencies of vibration brought about by the presence of structural damage to predict both the amount and position of damage in uniform beams. The altered values of frequency were used in a graphical solution, which detected the damage location and provided a parameter related to the magnitude of the damage present in the structure under examination. In the same year, the changes in the natural frequencies produced by cracks in a beam were compared with those caused by slots of the same depth and of different widths [6]. This research concluded that the difference between the frequency changes produced by cracks and slots is likely to be most severe when testing components with small defects since, for a cut of a given width, the ratio of width to depth of slot decreases as slot depth is increased.

In the early 1990s, A method of structural inspection based on the modal analysis of vibration response was proposed [7]. In this research, an interpretation of natural frequency changes derived from a perturbation of the equation of motion was used to indicate the location of deterioration. The method was demonstrated in experiments on a welded steel frame exposed to fatigue loading and on wire ropes damaged by saw cuts. Contemporaneously, Joshi and Madhusudhan [8] developed an approach to the free vibration of locally damaged beams by considering various homogeneous boundary conditions. Local material damage was modeled as an effective reduction in Young's modulus. The numerical results for the natural frequency showed that it was possible to arrive at a simple polynomial type of representation, which is the same for various boundary conditions and mode numbers. The results also showed that the nature of changes in frequency for the damage location is of the same type as local curvature in their undamaged equivalents.

A method for analyzing the effect of two open cracks on the frequencies of the natural flexural vibrations in a cantilever beam was presented by Ostachowicz and Krawczuk [9], who concluded that the positions of the cracks relative to each other significantly affected the changes in the frequencies of the natural vibrations when the relative depth of the cracks was equal. Wu et al. [10] explored the applicability of neural networks to the assessment of structural damage. A backpropagation ANN model was trained to recognize the frequency response of an undamaged structure and of structures in which individual members had sustained varying degrees of damage. However, the authors noted some complications in the application of this approach, such as the uncertainties of proper artificial neural network model training and the need to have access to a large amount of information if the network is to be trained adequately.

In parallel, Liang et al. [11] studied theoretical relationships between eigenfrequency changes and magnitudes, as well as the location of crack-induced damage. Later on, the same authors [12] developed a nondestructive evaluation (NDE) technique for the quantitative determination of the locations as well as the extent of the crack-induced damage in a beam. The technique required the field measurement of the eigenfrequencies of the in-service structure component containing the damaged areas. Later, Hassiotis and Jeong [13] proposed a method for estimating structural damage using measured changes in the natural frequencies. First-order perturbation of the eigenvalue problem was used to determine the relationship between the variation in the global stiffness matrix and the eigenvalues. In addition, these authors introduced an optimality criterion to solve these equations by minimizing the difference between the eigenvalue problems for the undamaged and damaged structures. In the same year, Morassi [14] showed that frequency sensitivity for any beam-like structure can be explicitly evaluated on the basis of the undamaged system by using a general perturbation approach.

Hu and Liang [15] explored two damage modeling techniques to develop an integrated NDE technique for detecting and quantifying the location and extent of multiple discrete cracks in a structure. The combined use of both models allowed global vibration characteristics to be used to identify multiple discrete cracks with sufficient local detail, such as the location and depth of cracks. Subsequently, the natural frequencies of a cracked simple supported uniform were found by an approximate analytical solution examining both bending and axial vibration [16]. The author stated that the analysis of the variation data of just two natural frequencies is enough for the identification of crack location. Later, Armon et al. [17] explored a method for the non-destructive detection and location of slots and cracks in a beam using rank-ordering of the modes according to fractional eigenfrequencies changes. This research used computer simulation to show that the rank-ordering of the eigenfrequencies shift is a function of damage location but, in the case of small cracks, does not depend on damage magnitude.

The following year, Zimmerman et al. [18] proposed an identification procedure using measured FRFs. The frequency response Minimum Rank Perturbation Theory (MRPT) approach was implemented in this work and tested on a two-dimensional eight-bay cantilevered truss. Similarly, crack-induced changes in the eigenfrequencies of a beam on elastic foundation were studied by Hasan [19]. A perturbation method was used to evaluate the first-order perturbation of the eigenfrequencies. Local flexibility, introduced by the crack in the cracked section, was represented by a massless rotational spring, whose stiffness depended on the severity of the crack. It was concluded that, while the eigenfrequencies were affected by the elastic foundation, their variations were not. In the meantime, an approach for determining crack detection using the non-linear character of a cracked vibrating beam was explored by [20]. The methodology was suggested by examining the response of a bilinear spring-mass system to excitation at two frequencies, such that the difference between the two frequencies was the resonant frequency of the system. The numerically generated steady-state response shows the effect of the opening and closing of the crack. The prominence of this non-linear effect was then correlated with crack position and depth.

A study of structural damage detection using measured FRF data was conducted by Wang et al. [21]. In this paper, a damage detection algorithm, based on nonlinear perturbation equations of receptance FRF data, was formulated to utilize an original analytical model and FRF data measured prior and posterior to an occurrence of damage. Bicanic and Chen [22] developed a procedure to identify the location and the extent of structural damage in framed structures using only a limited number of measured natural frequencies. The following year saw the presentation of one of the first works combining a natural-frequency based method and GAs for the detection of damage [23]. This research developed a combined genetic and eigensensitivity algorithm to identify the location and magnitude of damage in structures from measured natural frequencies and mode shapes of a structure. Contursi et al. [24] used a correlation coefficient termed Multiple Damage Location Assurance Criterion (MDLAC), to locate and estimate the absolute extent of damage. They demonstrated the effectiveness of the approach, using the numerical data for two truss structures and validating both location and sizing algorithms experimentally using a three-beam test structure.

Similarly, Schulz et al. [25] presented a technique to detect structural damage by monitoring vibration measurements. Thyagarajan et al. [26] investigated the optimization of FRFs as a means to diagnose damage using a minimum number of sensors on a structure. This research reported two limitations: first, it required high computational efforts and second, FRFs may not be precisely repeatable, due to variations in temperature, which change elastic modulus and cause boundary conditions to change. The effect of crack depth on the natural frequency of a prestressed fixed-fixed beam was also investigated [27] in research in which the authors suggested that the natural frequency of the system cannot be determined simply by treating the problem of a prestressed crack beam as a superposition of two separate effects (crack plus axial load). Later, Sampaio et al. [28] used the FRF curvature method to study the existence, localization and extent of damage in structures based only on the measured data, without the need for any modal identification. Almost at the same time, Fritzen and Bohle [29] proposed a procedure for damage detection and health monitoring in large scale structures using FRFs measurement.

2.2 Studies conducted during the 2000s

In early 2000, a simple nondestructive evaluation procedure was presented for identifying the location and size of a single crack in a one-dimensional beam-type structure using natural frequency data [30]. A paper by Vestroni and Capecchi [31] suggested an identification technique based on the analysis of all possible damage scenarios for a given number of damage locations. The authors reported that the approach, based on a comparison between analytical and experimental response quantities, was more versatile and easier to use along with finite element models. One year later, Morassi and Rollo [32] presented a diagnostic technique for identifying two cracks of equal severity in a simply supported beam under flexural vibration by analyzing the damage-induced changes in the first three natural frequencies. It was found that, even if symmetrical positions were ignored, cracks with different severity in two sets of different locations could produce identical changes in the first three natural frequencies. The work of Zang and Imregun [33] used measured FRFs as input data of ANNs to detect structural damage.

Khiem and Lien [34] developed a simplified method for evaluating the natural frequencies of beams with an arbitrary number of transverse cracks. This method was based on the use of a rotational spring model of crack and the transfer matrix method, which allowed the determinant of a 4×4 matrix to be calculated. The authors reported that their proposed method reduced the computer time needed to evaluate natural frequencies and that the frequency equation established is more general with respect to the boundary condition, including the elastic condition. The research concluded, furthermore, that natural frequencies are sensitive to the elastic boundary conditions only for spring constants ranged in some limited interval. Analogously, Chinchalkar [35] described a numerical method for determining the location of a crack in a beam of varying depth when the lowest three natural frequencies of the cracked beam are known.

Another important contribution regarding the use of FRF-based methodologies for structural damage identification in beam structures was developed by Lee and Shin [36], who studied the effects of the damage induced of higher vibration modes numerically. Shim and Suh [37] studied the crack identification problem for beam structures using a methodology of Pareto-based Continuous Evolutionary Algorithms for Multi-objective Optimization (MOPCEAs) to identify the crack profiles from the eigenfrequencies. Subsequently, Chen et al. [38] studied structural fault diagnosis and isolation using ANN based on response-only data. Multi-layer perceptron neural networks were used to diagnose messages on the faults introduced into structural systems. Zapico et al. [39] also employed ANNs to provide overall information about the location and amount of damage to each floor in composite frames caused by seismic loads. Owolabi et al. [40] discussed a simple method for predicting the location and depth of cracks based on changes in the first three natural frequencies and the corresponding amplitudes of the FRFs of beams.

Furthermore, Patil and Maiti [41] investigated a methodology based on frequency measurements used for detecting multiple open cracks in slender Euler–Bernoulli beams. Next, a statistical damage identification algorithm was proposed by Xia and Hao [42]. The statistics of the parameters were estimated using the perturbation method and verified using the Monte Carlo technique. In 2004, a structural damage identification method requiring only the FRF data measured in the damage state was developed for cylindrical shells [43]. A damage distribution function was used to represent the distribution and magnitudes of the local sites of damage within a cylindrical shell. Fang et al. [44], explored the use of FRFs as input data for a backpropagation ANN used to detect structural damage. The methodology proposed by these authors was capable of detecting single and multiple cracks in a benchmark beam structure, combining accuracy in predicting damage location and severity with learning efficiency. The concept of FRF-based minimum rank perturbation theory (MRPT) for structural model correlation and health monitoring was also developed by Zimmerman et al. [45].

Another paper that discussed the combined use of FRFs and ANNs for seismic damage identification on a 38-story building model was conducted by Ni et al. [46]. Loya et al. [47] obtained natural frequencies of bending vibrations of Timoshenko cracked beams while Xu et al. [48] used an iterative algorithm to identify the location and extent of damage in beams using only the changes in their first several natural frequencies. A hybrid neuro-genetic algorithm for damage assessment was proposed by Sahoo and Maity [49]. This algorithm was projected in order to automate the design of neural networks for different types of structure. Additionally, Peng et al. [50] introduced the concept of Nonlinear Output Frequency Response Functions (NOFRFs) to detect cracks in beams using frequency domain information. The results obtained in this research showed that NOFRFs are a sensitive indicator of the presence of cracks providing the level of excitation is of appropriate intensity.

The following year, a fault diagnosis method based on GAs and a model of a damaged (cracked) structure was proposed [51]. Peng et al. [52] used NOFRFs to develop an analysis of the dynamic behavior of beams with a closing crack in the frequency domain. Faverjon and Sinou [53] proposed using the FRF and the Constitutive Relation Error updating method (CRE updating method) to detect double and triple open transverse cracks for a simply supported beam. The article demonstrated that the CRE updating method may detect not only the number of cracks but also their locations and depths. Metaheuristic techniques became more important from 2009 onwards. A hybrid Particle Swarm Optimization – Simplex Algorithm (PSOS) model-based damage identification procedure using frequency domain data was proposed by Begambre and Laier [54], while Esfandiari et al. [55] worked on a method using vibration data for structural mass and stiffness estimation including damping effects. Lee [56] developed an efficient method using natural frequencies for the identification of multiple cracks in a beam. Liu et al. [57] proposed some modifications of the existing methods within the "shape signal comparison-based" approach, focusing on the FRF shape-based methods and the theoretical explanation of their use in structural damage localization.

Dilena and Morassi [58] studied a dynamic Euler–Bernoulli model of a composite beam with a shearing-type strain energy in the connection zone to identify damage and interpret the experimental results they had reported previously [59]. In the meantime, White et al. [60] described a technique based on frequency response for the detection of debonding in composite bonded patches. Chatterjee [61] analyzed the use of Volterra series response representation for developing a quantitative damage assessment technique for a cantilever beam with an edge crack. Yang and Wang [62] proposed a new method for damage detection based on the concepts of the Natural Frequency Vector (NFV) and Natural Frequency Vector Assurance Criterion (NFVAC). Also in 2010, Singh and Tiwari [63] developed a two-step multi-crack identification GA in a shaft system using transverse frequency response functions.

2.3 More recent advances in frequency-based SHM

One of the first applications using both natural frequencies and an evolutionary algorithm inspired by a model of natural evolution called the bee algorithm (BA) alongside PSOs for crack detection in beams was proposed by Moradi et al. [64]. Numerical and experimental studies were designed to predict a single open edge-crack in cantilever beams. The paper of Li et al. [65] focused on a vibration-based damage identification method, which utilized dimensionally reduced residual FRF data in combination with neural networks to identify the location and severity of damage in numerical and experimental beam structures. Similarly, an optimization procedure to detect the location and extent of multiple sites of structural damage was presented by Seyedpoor [66]. The following year, Sayyad and

Kumar [67] explored a simple and accurate method to detect a crack by measuring natural frequencies in a cracked simply supported beam. Next, Huang et al. [68] explored two methods for system identification and damage detection of controlled building structures equipped with semi-active friction dampers by way of model updating based on FRFs. For their part, Greco and Pau [69] focused on model updating and damage identification of elastic frames composed of Euler beams.

Furthermore, Samali et al. [70] explored ways of identifying the location and severity of notch-type damage in a two-story steel frame structure, while FRFs and ANN were explored by Majumdar et al. [71], who presented a method for detecting and assessing structural damage in truss structures from changes in natural frequencies using Ant Colony Optimization (ACO). The results obtained by this research indicated that the first three natural frequencies are enough to locate and assess damage to a satisfactory level of precision. Subsequently, in 2013, a technique using a damage index derived from FRFs with a three-stage ANN method was proposed and validated in a 10-story frame [72]. Dackermann et al. [73] examined a structural health monitoring technique utilizing pattern changes in FRFs as input parameters for a system of ANN to assess the structural condition of a structure. Once again, PSO optimization using FRF as input was employed to locate and quantify damage in structures [74]. Zhou et al. [75] focused their research on using a Probabilistic Neural Network (PNN) for damage localization in two different cable-supported bridges from simulated noisy modal data. Subsequently, a modified PSO with a new operator and continuous damage variables was proposed by Nouri et al. [76]. A new method for single crack localization in frames was illustrated by Labib et al [77], while Moezi et al. [78] implemented a Modified Cuckoo Optimization Algorithm (MCOA) for open edge-crack detection in Euler–Bernoulli cantilever beams.

An inverse analysis of the crack identification problem using a modified PSO technique was explored by Jena and Parhi in [79] and the dependability of the proposed algorithm investigated by comparing the results of the MPSO with those obtained using a methodology based on Differential Evolution (DE). The results obtained indicated that crack locations and depths were more accurately determined by the proposed algorithm than those obtained using DE. Seyedpoor et al. [80] used a Differential Evolution Algorithm (DEA) to solve the optimization-based damage detection problem. An early structural damage assessment using an improved frequency evaluation algorithm was proposed by Gillich et al. [81]. Lin's paper [82] examined how flexural cracks affect measured vibration properties such as FRFs and how these may be used to locate flexural cracks and so identify crack parameters such as depth. In late 2016, a novel concept known as the Frequency Shift (FRESH) path was introduced by Wang et al. [83]. The FRESH path combines the effects of frequency shifting and amplitude changing into one space curve, providing a tool for analyzing structure health status and properties.

Table 1 summarizes the computational optimization techniques discussed in this paper that have been employed to solve the inverse damage detection problem.

Table 1.
Computer-aided techniques used in frequency-based SHM through the years

Author	Technique
Preliminary studies	
Wu et al. (1992)	ANN
Penny and Garvey (1998)	GA
Studies in the 2000s	
Zang and Imregun (2001)	ANN
Shim and Suh (2003)	Evolutionary Algorithms
Chen et al. (2003)	ANN
Zapico et al. (2003)	ANN
Fang et al. (2005)	ANN with learning rate improvement.
Ni et al. (2006)	ANN
Sahoo and Maity (2007)	hybrid neuro-GA.
Vakil-Baghmisheh et al. (2008)	GAs
Begambre and Laier (2009)	PSO
More recent advances in frequency-based SHM	
Singh and Tiwari (2010)	GA
Moradi et al. (2011)	BA and PSO
Li et al. (2011)	ANN
Seyedpoor (2011)	PSO
Samali et al. (2012)	ANN
Majumdar et al. (2012)	ACO
Bandara et al. (2013)	ANN
Dackermann et al. (2013)	ANN
Mohan et al. (2013)	PSO
Zhou et al. (2014)	PNN
Nouri et al. (2014)	Modified PSO
Moezi et al. (2015)	MCOA
Jena and Parhi (2015)	MPSO and DE
Seyedpoor et al. (2015)	DEA
Moezi et al. (2018)	COA-NM
Zenzen et al. (2018)	GA and BTA
Khatir et al. (2018)	PSO-FEM
Zenzen et al. (2020)	ANN

Source: The Authors

A procedure for detecting structural damage using transmissibility together with hierarchical clustering and similarity analysis was proposed by Zhou et al. [84]. Transmissibility is derived from the structural dynamic responses (frequency domain measured data) characterizing the structural state. Subsequently, Zhou et al. established an output-based structural damage detection methodology by using correlation analysis together with transmissibility [85]. Gillich et al. [86] presented a procedure to enhance the accuracy of frequency identification and allow damage to be located precisely. Next, a methodology based on a hybrid Cuckoo-Nelder-Mead Optimization Algorithm (COA-NM) was used by Moezi et al. [87] to estimate number, location and depth of open-edge cracks in cantilever Euler-Bernoulli beams. Lin and Ng [88] examined how second-order FRFs can be derived and employed for improved detection and assessment of structural damage caused by the initiation and development of breathing cracks.

Zenzen et al. [89] introduced a technique for damage identification in beam-like and truss structures using FRF data coupled with optimization techniques; GA and the Bat Algorithm (BTA) were used to estimate the location and severity of damage. In the same way, Khatir et al. [90] presented a PSO-FEM technique based on experimentally measured natural frequencies that were used to explore the variation in local flexibility near the crack for the detection and localization of an open crack in beam-like structures. For the purpose, they adopted the Fourier transform to improve frequency resolution. On the other hand, Zhou et al. [91] developed an early-stage damage detection procedure using transmissibility compressed by PCA, along with a distance measure and correlation analysis. Finally, a modified damage indicator using transmissibility techniques to improve the Local Frequency Response Ratio (LFCR) combined with ANN was addressed by Zenzen et al. [92] whose results demonstrated the good performance of the indicator for locating damage as well as reductions in computational time.

3. Conclusions

This paper presented a chronological literature review of the frequency-based methodologies for the detection of structural damage written over the last forty years. Before 2000, most of the works referenced in this paper focused on experimental measurements of frequency changes made on actual structures. By contrast, random search procedures have been employed to minimize the difference between the eigenvalue problems for the undamaged and damaged structures, including: artificial neuronal networks (ANNs), genetic algorithms (GAs), particle swarm optimization (PSO), ant colony (AC), bee algorithm (BA), differential evolution algorithm (DEA), cuckoo optimization algorithm (COA), bat algorithm (BTA), and other multiple changes or modification to these methodologies. Finally, this review provides a wider understanding of frequency-based methods for structural damage detection. It may therefore serve as a useful reference for further investigations.

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