mathematics

Article

Efficient Structural Damage Detection with Minimal Input Data: Leveraging Fewer Sensors and Addressing Model Uncertainties

Fredi Alegría [1], Eladio Martínez [1], Claudia Cortés-García [1], Quirino Estrada [2], Andrés Blanco-Ortega [1] and Mario Ponce-Silva [1,*]

[1] Tecnológico Nacional de México-CENIDET, Cuernavaca 62490, Morelos, Mexico; d15ce001@cenidet.tecnm.mx (F.A.); claudia.cg@cenidet.tecnm.mx (C.C.-G.)
[2] Instituto de ingeniería y Tecnología, Universidad Autónoma de Ciudad Juárez, Ciudad Juárez 32310, Chihuahua, Mexico
* Correspondence: mario.ps@cenidet.tecnm.mx

Abstract: In the field of structural damage detection through vibration measurements, most existing methods demand extensive data collection, including vibration readings at multiple levels, strain data, temperature measurements, and numerous vibration modes. These requirements result in high costs and complex instrumentation processes. Additionally, many approaches fail to account for model uncertainties, leading to significant discrepancies between the actual structure and its numerical reference model, thus compromising the accuracy of damage identification. This study introduces an innovative computational method aimed at minimizing data requirements, reducing instrumentation costs, and functioning with fewer vibration modes. By utilizing information from a single vibration sensor and at least three vibration modes, the method avoids the need for higher-mode excitation, which typically demands specialized equipment. The approach also incorporates model uncertainties related to geometry and mass distribution, improving the accuracy of damage detection. The computational method was validated on a steel frame structure under various damage conditions, categorized as single or multiple damage. The results indicate up to 100% accuracy in locating damage and up to 80% accuracy in estimating its severity. These findings demonstrate the method's potential for detecting structural damage with limited data and at a significantly lower cost compared to conventional techniques.

Keywords: structural damage; damage identification; genetic algorithms; uncertainties; incomplete data; MATLAB

MSC: 65Z05

Citation: Alegría, F.; Martínez, E.; Cortés-García, C.; Estrada, Q.; Blanco-Ortega, A.; Ponce-Silva, M. Efficient Structural Damage Detection with Minimal Input Data: Leveraging Fewer Sensors and Addressing Model Uncertainties. *Mathematics* **2024**, *12*, 3362. https://doi.org/10.3390/math12213362

Academic Editor: Jonathan Blackledge

Received: 1 October 2024
Revised: 14 October 2024
Accepted: 24 October 2024
Published: 26 October 2024

1. Introduction

Structural damage detection has garnered significant attention over the past few decades due to its importance in ensuring the safety and longevity of civil infrastructures. Damage detection methodologies can generally be categorized into local and global methods. While local methods offer high precision in identifying damage location, they often require predefined search regions and unrestricted access to structural components, which is not always feasible. On the other hand, global methods, particularly those relying on vibration response measurements, have proven more practical for large structures where accessibility and instrumentation are limited. These vibration-based methods utilize either raw signals, such as acceleration and velocity, or processed data like modal frequencies and shapes to detect damage, offering a non-destructive means of structural health monitoring [1–13]. Despite their benefits, these methods face challenges related to the complexity and non-linear behavior of structures [14]. Recent developments in the use of neural networks for predicting structural behaviors have demonstrated a strong ability to handle large datasets and adapt to the physical conditions of the environment. In