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Frequency Analysis of Cracked Beams Using Machine Learning Algorithms

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Abstract

This study investigates the effect of the presence of two cracks in a beam on its dynamic characteristics, particularly its natural frequencies. To this end, the natural frequencies of the beam were calculated using a numerical solution based on the Rayleigh method, considering the depth and location of the cracks. The mathematical relationships were then implemented in Python, and through iterative computations for different inputs, a suitable dataset was generated for training machine learning algorithms. The algorithms examined in this study include Random Forest, Gradient Boosting, Multilayer Perceptron, and Decision Tree. The main innovation of the research is the application of a grid search method to determine the optimal amount of data required for each algorithm, introducing a comparison criterion referred to as the “required data volume.” The results indicate that increasing the dataset size generally improves prediction accuracy, and single-output algorithms perform more accurately than multi-output models. Ultimately, the Gradient Boosting algorithm with an accuracy of 84.10% and the Random Forest algorithm with an accuracy of 83.73% showed the best performance in predicting the natural frequency of the beam.

Keywords:

Machine learning, Cracked beam, Natural frequency, Python, Multi-layer perceptron, Gradient boosting regression.

1. Introduction

The evaluation, identification, and monitoring of structural health, especially cracks and damage, play a significant role in ensuring the safety and durability of structures. Cracks increase stress concentration and flexibility in structures, causing a reduction in natural vibration frequencies and inducing deformation. Thus, developing advanced diagnostic methods to facilitate early crack detection and analyze their effects is essential. With technological advancements in machine learning algorithms and sensor data availability, researchers have designed intelligent models that accurately identify crack locations and severity while analyzing their impact on the dynamic behavior of structures [1–3].

This study integrates traditional numerical and analytical methods with advanced artificial intelligence algorithms such as Random Forests (RF), Artificial Neural Networks (ANN), and Gradient Boosting Models (XGB) to provide a deeper understanding of the effects of crack patterns on structural vibrations. Data collected through experimental testing and numerical analysis, such as employing Euler-Bernoulli beam theory and composite material modeling, enable accurate prediction of the natural frequencies of cracked structures. Related studies [4–6] highlight that these methods, minimizing prediction errors to below 1%, provide highly effective tools for structural health analysis and management.

Recent progress in combining deep learning techniques (such as Convolutional Neural Networks) with vibration and image data analysis has introduced new capabilities for diagnosing and assessing damage in complex structures. For example, research on fiber-reinforced plastic beams and steel beams subjected to complex loading conditions has shown that utilizing these tools achieves detection accuracy levels of 95% or higher [7–10]. This work, by integrating artificial intelligence with numerical and experimental methods, introduces novel approaches for identifying and evaluating structural damage, paving the way for advancements in structural health management and design.

2. Methodology

2.1. Physical System Description

A simple beam with two cracks is defined with a length (l), height (h), and width (b). The cracks are located at positions (x_{c1}) and (x_{c2}) with respective depths (d_1) and (d_2). The sectional flexibility of the cracked beam is calculated based on the cracks' depths (a_j), reflecting the direct impact of cracks on the beam's stiffness. The Rayleigh method was

employed to calculate the natural frequencies of the beam, which are directly linked to the potential and kinetic energy of the structure.

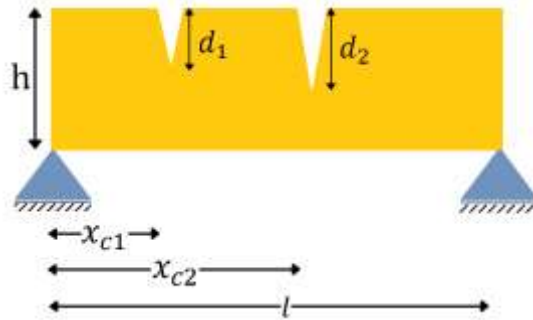


Figure 1. The investigated beam with two cracks of varying depths.

2.2. Machine Learning in Problem Solving

To analyze and predict the beam's behavior, machine learning algorithms such as RFR, GBR, MLP, and DTR were implemented. These algorithms were evaluated for modeling relationships between input and output data while optimizing predictive accuracy. Performance was assessed using error metrics like (R^2), MAE, and MSE, with GBR and RFR delivering the best predictions.

2.3. Error Analysis, Noise Effect, and Uncertainty

To examine model robustness, the impacts of Gaussian and white noise on the input data were analyzed, showcasing the algorithms' resilience to data fluctuations. Error calculations and random uncertainty analysis played an essential role in evaluating the models' capability to handle variability in data. This analysis was crucial for improving model efficacy in complex real-world applications.

3. Results and Discussion

This study investigates the impact of cracks on the natural frequencies of beams and evaluates the application of machine learning algorithms for accurate predictions. The results revealed that Gradient Boosting Regression (GBR) and Random Forest Regression (RFR) outperform other algorithms due to their high accuracy and closer alignment with the reference curve. Additionally, the depth of cracks and a reduction in the number of main input parameters influenced prediction accuracy, where GBR achieved the highest performance with 97.75% accuracy. Simulations showed that adding Gaussian and white noise did not significantly affect prediction accuracy, and the algorithms maintained high stability.

Moreover, comparisons indicated that GBR, with optimized hyperparameters, excelled in handling complex datasets and minimizing uncertainties. The findings of this research not only contribute to the development of a reliable framework for analyzing the natural frequencies of cracked beams but also serve as a practical tool for fast decision-making in structural maintenance and prevention of catastrophic failures. Future developments may include the creation of a user interface for industrial applications, evaluation of the time-dependent behavior of cracks, and detailed study of varying crack geometries.

The beam under investigation is characterized by two cracks with non-identical depths and locations. Given the sensitivity of natural frequencies to structural integrity, these parameters are adopted as the objective variables. Consequently, an ensemble of machine learning models is employed to map the relationship between crack configurations and frequency shifts, with the results discussed and compared hereafter.

Figure 2 illustrates the relationship between the first crack depth and the beam's fundamental natural frequency, providing a comparison between numerical simulations and various machine learning techniques. The black curve serves as a benchmark, establishing a reference against which the performance of the AI models is evaluated. While the AI algorithms generally follow the expected physical trend, they exhibit significant fluctuations relative to the reference curve [11] as the crack depth increases. Such oscillations suggest that certain models encounter difficulties in accurately capturing the inherent complexities of the dataset. Nevertheless, the Gradient Boosting Regression (GBR) and Random Forest Regression (RFR) models demonstrate superior performance, characterized by their relative stability and closer alignment with the reference data across the entire range.

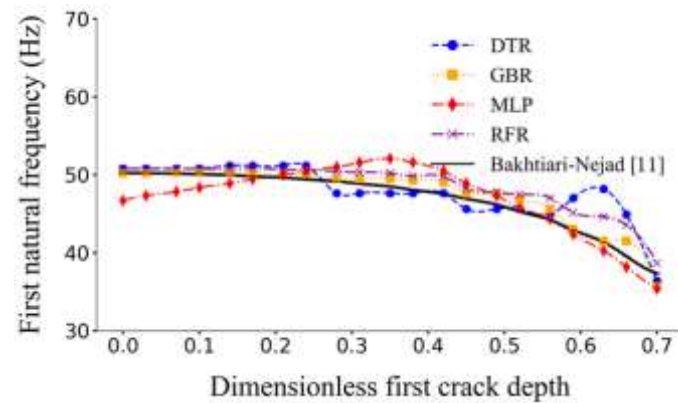


Figure 2. The effect of the first crack depth on the first natural frequency of a beam with two cracks, where the locations of the first and second cracks are 0.3 and 0.6, respectively, and the depth of the second crack is 0.5 from the beam surface.

Figure 3 provides a comparison of the accuracy of two selected machine learning algorithms using the R-squared (R^2) method: GBR and RFR, evaluated at different dataset sizes ranging from 50 to 1500. RFR shows strong performance, with good accuracy on smaller datasets, and its accuracy increases as the dataset size grows for prediction. However, GBR consistently outperforms RFR across the board and ultimately achieves its best performance with larger dataset volumes. In this research, both algorithms show a positive response to the increase in data volume, leading to an improvement in their predictive accuracy.

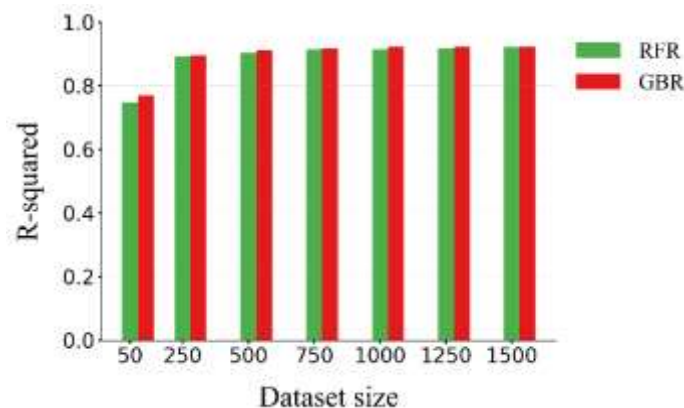


Figure 3. Effect of dataset size on accuracy (using the R-squared method) for machine learning algorithms.

By adding noise to the data, the evaluation of machine learning algorithms can be performed more effectively. As shown in Figure 4, the use of Gaussian noise results in a more precise representation of the data and clarifies the accuracy of the predictions. The added noise is centered around a mean value, allowing the fundamental trends to be preserved while introducing a controllable level of variability. It is observed that Gaussian noise more effectively enhances the clarity of prediction accuracy and demonstrates its superior performance in maintaining the integrity of the underlying signal amid randomness. By comparing Figure 4 with Figure 2, it can be seen that adding noise does not significantly affect the algorithms' predictions, indicating that the algorithms are resistant to noise.

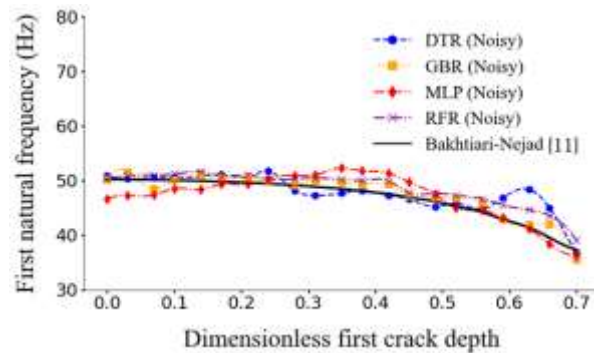


Figure 4. Effect of the first crack depth on the first natural frequency of a beam with two cracks, where the locations of the first and second cracks are 0.3 and 0.6, respectively, and the second crack depth is 0.5 from the beam surface, based on Gaussian noise.

4. Conclusions

This study evaluates the performance of multiple machine learning algorithms, including Random Forest Regression (RFR), Gradient Boosted Regression (GBR), Multilayer Perceptron (MLP), and Decision Tree Regression (DTR), for predicting the natural frequencies of a beam with two cracks. The comparison with a numerical-analytical method [11] demonstrates the high accuracy of the proposed approach. Key findings include: increasing the dataset size enhances accuracy to a certain extent; single-parameter predictions outperform multi-parameter outputs; GBR achieves 97.75% accuracy, and RFR follows with 95.74%; datasets larger than 1000 have minimal impact on accuracy but reduce computational efficiency; greater accuracy is observed at smaller crack depths; DTR exhibits the lowest accuracy at 83.60%; and all algorithms maintain over 80% accuracy even with added noise. Notably, RFR demonstrates minimal uncertainty across all frequencies, particularly the first and second natural frequencies (ω_1 and ω_2). These findings contribute to understanding the mechanics of cracked beams, provide a reliable framework for natural frequency predictions, facilitate early structural fault detection, and enable proactive maintenance strategies to prevent catastrophic failures.

5. References

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