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Vehicle-Bridge Interaction Simulation and Damage Identification of a Bridge Using Responses Measured in a Passing Vehicle by Empirical Mode Decomposition Method

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Abstract

To prevent early bridge failures, effective Structural Health Monitoring (SHM) is vital. Vibration-based damage assessment is a powerful tool in this regard, as it relies on changes in a structure's dynamic characteristics as it degrades. By measuring the vibration response of a bridge due to passing vehicles, this approach can identify potential structural damage. This dissertation introduces a novel technique grounded in Vehicle-Bridge Interaction (VBI) to evaluate bridge health. It aims to detect damage by analyzing the response of passing vehicles, taking into account VBI. The theoretical foundation of this method begins with representing the bridge's superstructure using a Finite Element Model and employing a half-car dynamic model to simulate the vehicle with suspension. Two sets of motion equations, one for the bridge and one for the vehicle are generated using the Finite Element Method, mode superposition, and D'Alembert's principle. The combined dynamics are solved using the Newmark-beta method, accounting for road surface roughness. A new approach for damage identification based on the response of passing vehicles is proposed. The response is theoretically composed of vehicle frequency, bridge natural frequency, and a pseudo-frequency component related to vehicle speed. The Empirical Mode Decomposition (EMD) method is applied to decompose the signal into its constituent parts, and damage detection relies on the Intrinsic Mode Functions (IMFs) corresponding to the vehicle speed component. This technique effectively identifies various damage scenarios considered in the study.

Keywords

Structural Health Monitoring, Vibration-Based Damage Identification, Vehicle-Bridge Interaction, Finite Element Model, Empirical Mode Decomposition

1. Introduction

Damage refers to any alteration in the structure that negatively affects its performance or safety, such as material deterioration or boundary condition degradation. Civil structures like bridges are susceptible to natural and human-induced damage over time. Older structures are at risk of natural failure due to structural aging. Overloading on bridges and environmental effects can also lead to potential failures of bridge and structural components.

Various scholars including Maeck (2003), Yang *et al.* (2004, 2014), Hou *et al.* (2014), Amezquita-Sanchez and Adeli (2016), O'Brien *et al.* (2016), and Sun *et al.* (2016) have proposed diverse analysis methods for damage identification in bridge structures [1]-[7]. Structural Health Monitoring (SHM) techniques have emerged as an appealing alternative to traditional damage detection methods, given their potential for enhancing the safety, serviceability, and cost-efficiency of crucial infrastructure throughout its lifecycle. The implementation of Structural Health Monitoring (SHM) might be likened to the practice of monitoring the quality of drinking water to increase safety and mitigate potential threats to the community [8] [9] [10].

The growing recognition of the importance of dependable structural damage detection systems highlights the critical requirement for integrated approaches that encompass multiple aspects of infrastructure development, in line with the overarching principles of infrastructure resilience and sustainability. Waste management is of paramount importance when it comes to bolstering the resilience of infrastructure [11] [12] [13] specifically by facilitating the recycling of organic waste for the generation of biogas [14] [15]. By adopting this environmentally sustainable method, the ecological consequences of waste are mitigated, and a valuable energy source is generated. Concurrently, the implementation of waste byproduct utilization, such as cotton dust, bolsters the circular economy and contributes to the sustainability of infrastructure [16]. Moreover, it is critical to guarantee access to clean water, as this facilitates efficient waste management and enhances hygiene [17]. This is consistent with our comprehensive strategy for bolstering infrastructure resilience. Furthermore, the incorporation of machine learning into green manufacturing processes improves both efficiency and environmental friendliness, which is in perfect harmony with our overarching objectives of sustainable infrastructure and environmental accountability [18] [19].

Having accurate information about bridge health conditions and identifying potential bridge damage is crucial. To analyze the behavior several numerical approaches are used [20] [21] [22] [23] [24]. Rigorous site investigations and laboratory testing are conducted to investigate the prevailing soil condition [25] [26] [27]. Also, the seismic performances are analyzed using available site response analysis data [28] [29]. This allows for better planning for bridge maintenance, minimizing traffic disruption, and preventing early repairs. Early detection of damage induced by vehicle vibrations provides an opportunity to implement countermeasures, including the use of stock-bridge dampers or the integration of smart materials with high damping capacity, such as shape memory alloys [30] [31]. Typically, bridges have been monitored for damage using periodic visual inspections. These methods are also utilized in the field of environmental engineering, specifically for the purpose of detecting and controlling nitrogen levels in landfill leachate to mitigate the growth of algae [32] [33]. The objective is to achieve early detection and prevention measures that guarantee long-term safety and maintain ecological equilibrium. While these methods are generally effective, they have significant drawbacks. For example, there can be variability in judgment between different bridge inspectors, making damage quantification difficult. Also, inspections require an inspector to physically be at the bridge site. Failures could occur between inspections, and initial damage might go unnoticed. Due to inconsistent bridge maintenance and challenges in inspections, numerous bridge collapses have occurred globally. Also, in some cases due to natural calamities [34] [35] [36] [37]. The Genoa bridge collapse, which resulted in forty-three fatalities in August 2018, is a recent example. This highlights the urgent need for reliable structural damage detection systems.

The damage detection method proposed in this paper employs the dynamic characteristics of structures. Various studies focused on service life [38], structural ability [39] [40] as well as clay sand [41] [42] [43] [44] [45] for the construction of buildings. However, the increase in the weight and speed of vehicles in recent years has escalated the dynamic influence on bridges. The dynamic responses generated by vehicles crossing bridges and viaducts can serve as a valuable resource for monitoring the structural health of such structures. To quantify the dynamic properties of vehicles, previous studies has utilized an Arduino microcontroller-based machine that measures vehicle speed and jerking while being attached to operating vehicles [46] [47] [48]. Dynamic models are employed to assess various aspects, such as the fatigue life of different structural parts, environmental vibration issues, and the safety and comfort of traffic on bridges [49] [50]. Vehicle-bridge interaction (VBI) is utilized to determine the vehicle-induced dynamic responses of bridges. The VBI dynamic model depends on numerous factors like the dynamic properties of bridges, vehicle speed, the dynamic properties of the vehicle, and road pavement conditions. The main purpose of this paper is to identify damaged locations by analyzing the response of vehicles on the bridge.

2. Methodology

This section discusses the modelling and the damage detection method adopted in this study.

2.1. Vehicle Modeling

In this study, a Half car model has been taken as the design vehicle as in Figure 1. The vehicle model consists of a total of four degrees of freedom (DOF). Among them, the body of the vehicle has two DOFs, vertical vehicle body displacement, y_s and pitching rotation θ_s. This rotation data can be measured by the sensor installed in the vehicle. The front and rear wheel also have a set of DOFs for vertical displacement, y_{t1} and y_{t2} respectively. Then, following D'Alembert's principle, a set of kinetic equilibrium functions are formulated for each DOF.

$$[M_v]\{\ddot{y}_v(t)\}+[C_v]\{\dot{y}_v(t)\}+[K_v]\{y_v(t)\}=\{F_v\} \tag{1}$$

2.2. Bridge Modeling

The bridge is modeled according to the Finite Element Method (FEM) as shown in Figure 2. The bridge is a simply supported bridge and it has a constant flexural rigidity, EI along the span, where, E and I refer to Young's modulus and the moment of inertia of the bridge cross section respectively. The mass per unit length of span is defined by m. The EOM for the bridge is formulated as

$$\ddot{\eta}_n(t)+2\zeta_n\omega_n\dot{\eta}_n(t)+\omega_n^2\eta_n(t)=-\frac{1}{M_n}\{\varphi_n\}^{\mathrm{T}}\{F_b(x,t)\}\delta(x-vt) \tag{2}$$

where, $n=1,2,3,\cdots,N$.

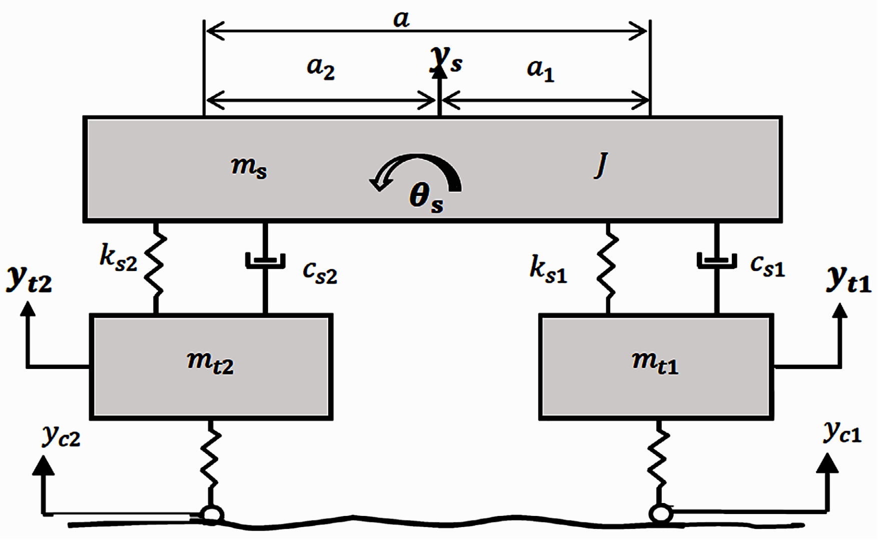

Figure 1. Half car vehicle model.

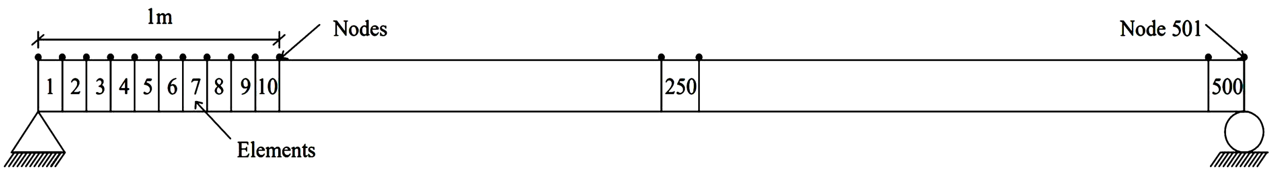

Figure 2. Bridge model.

2.3. Vehicle-Bridge Interaction

Two distinct sets of differential equations have been developed for the vehicle and the bridge, respectively. These equations are coupled to establish an interaction between the vehicular and bridge systems. To foster this interaction, compatibility conditions are applied at contact points, and coupled equations of motion are formulated. Here, **Figure 3** depicts the model of coupled vehicle-bridge vibration.

$$\left[M(t)\right]\left\{\ddot{Y}\right\}+\left[C(t)\right]\left\{\dot{Y}\right\}+\left[K(t)\right]\left\{Y\right\}=\left\{Q(t)\right\} \tag{3}$$

2.4. Damage Identification Method

2.4.1. Empirical Mode Decomposition (EMD)

The EMD technique is an innovative tool for processing signals that can break down any type of signal, even non-stationary or nonlinear ones, into multiple Intrinsic Mode Functions (IMFs). This method has been employed in the past for identifying structural damage and monitoring structural health. To extract an IMF, a process called "sifting" is performed. This involves:

1) Identifying all local maxima and minima in the original time signal.

2) Connecting all the local maxima and minima with cubic splines to form the upper and lower envelopes.

3) Calculating the mean value of the two envelopes and subtracting this from the original signal.

The resultant difference between the original time history and the mean value is considered to be the IMF, assuming it meets certain conditions: the number of extrema and zero crossings must be either equal or differ by at most one, and the mean value of both the envelopes defined by the local maxima and minima should be zero at every point. The sifting continues until the residue becomes insignificantly small or it turns into a monotonic function. The original time signal can then be represented as the sum of the IMFs and the final residue. The first IMF encapsulates the highest frequency content of the original signal, while the final residue contains the lowest frequency. The method of EMD is used in this section to decompose the theoretical responses derived from the quarter car model's VBI. The IMFs and their Fast Fourier Transform (FFT) spectra for displacement are also extracted. It is clear from the FFT spectrum of the first IMF that it relates to the bridge's first natural frequency being affected by the vehicle speed, while the other IMFs are related to the speed pseudo-frequency part of the signal. Hence, by eliminating the first IMF from the original signal, the speed pseudo-frequency part that is sensitive to damage can be extracted.

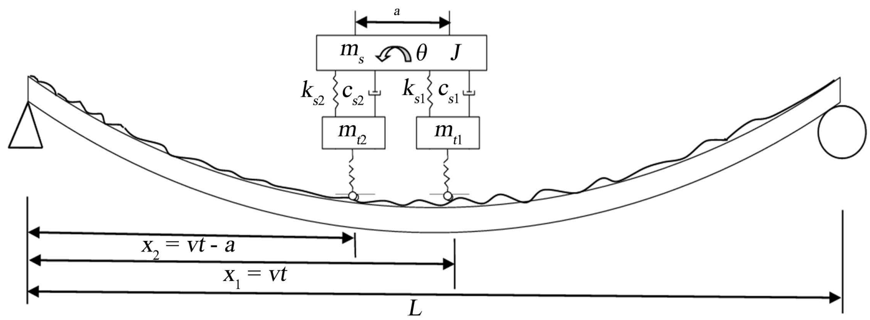

Figure 3. The model of coupled vehicle-bridge vibration.

2.4.2. IMF-Based Damage Indicator

The difference between the speed pseudo-frequency components of the acceleration signals for healthy and damaged structures is damage-sensitive. An IMF-based damage indicator, a parameter sensitive to damage, is introduced in this section to deal with the interference caused by the road surface profile. The EMD is applied to the difference between the acceleration signals for the healthy and damaged structures. The first IMF corresponds to the bridge's natural frequency from the frequency content of the IMFs. Therefore, the other IMFs correspond to the speed pseudo-frequency part of the signal. The damage indicator is obtained by summing all IMFs except the first one. The results for both damage scenarios are displayed using displacement responses. Three different crack sizes are considered for both damage scenarios, and a clear peak near the damage location can be seen when the displacement signal is used in all cases.

3. Damage Identification

The differential equations representing the VBI system have time-varying coefficients. The Newmark's β method is used to solve the coupled formulation resulting from these differential equations of bridge and vehicle subsystems. This numerical method segments time into various steps with an increment of Δt. Subsequently, for all damage scenarios discussed above, the time history responses of bridge displacement at different sensor locations are determined. The roughness of the Class A-B deck surface is taken into account. As per Figure 4, the response considered here is the rotational displacement of the vehicle body. Damage in the bridge is introduced via a reduction in stiffness.

3.1. Damage Identification for Scenario D1

The rotational displacement response of the vehicle body is taken for both healthy and damaged conditions to apply the EMD. From Figure 5 and Figure 6, The IMFs obtained from the EMD and their FFT spectra are shown in Figures for rotational displacement. As per Figure 7, it can be seen from the FFT spectrum of the first IMF that it is associated with the bridge's first natural frequency (Table 1). The remaining IMFs are related to the speed pseudo-frequency part of the signal.

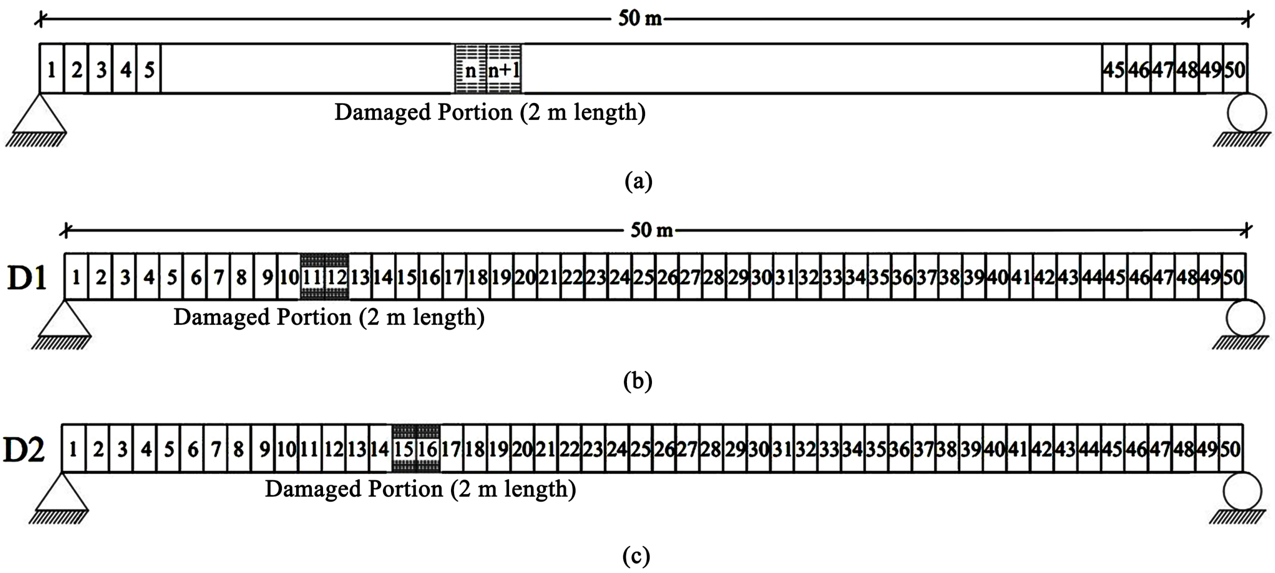

Figure 4. Introducing damage on the bridge at (a) two arbitrary elements, (b) element number 11 and 12, (c) element number 15 and 16.

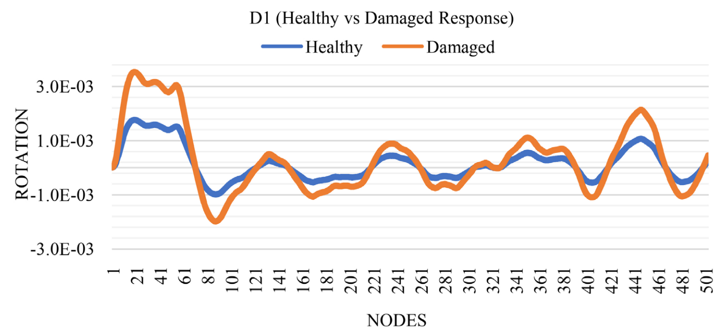

Figure 5. Responses and IMFs of rotational displacement (Healthy vs Damaged).

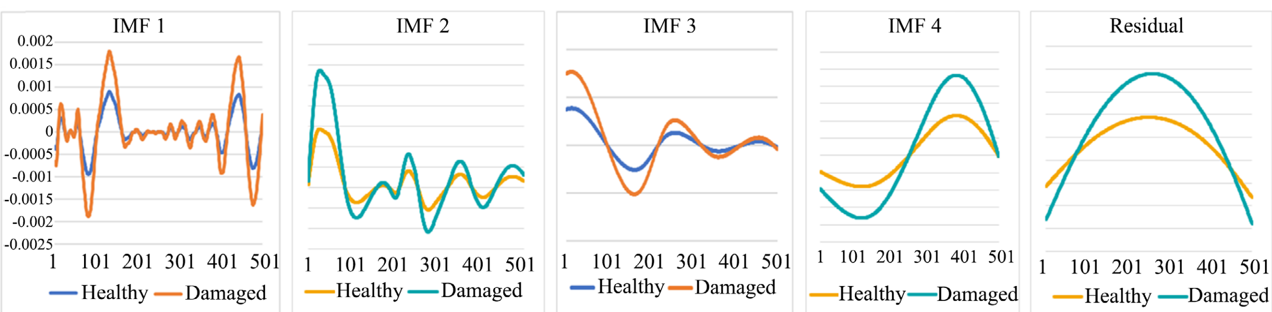

Figure 6. FFT of the rotational displacement.

Table 1. Frequencies of bridge and vehicle.

Bridge Freq.	Vehicle Freq.	Speed Pseudo Freq.
2.008	1.05388	1.396
8.03	1.13376	
18.07	8.73176	

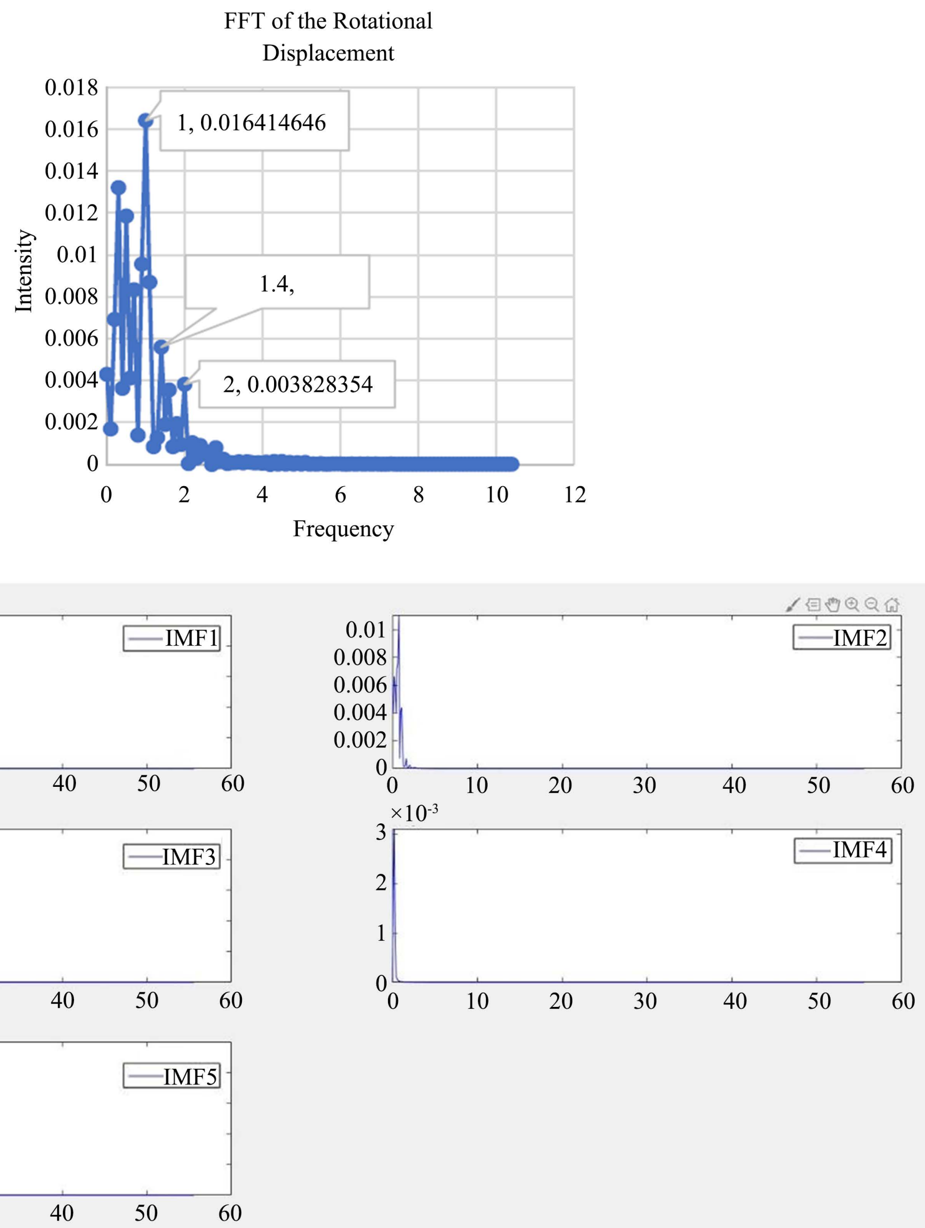

Figure 7. FFT spectrum of the different IMF.

Also, from Figure 8, the first damage on the bridge was introduced by reduction of stiffness at a distance of 11 m to 12 m from the left support. Now difference between the added IMFs except 1st gives the damaged location by removing the first IMF from the original signal, the speed pseudo-frequency part will remain which is to be sensitive to damage and can be extracted from the signal.

Now, the following Figure 9 will show the damage case (D1) where the prominent peak distinguishes the damage position for damage severity cases of 25%, 40% and 50%. After analysis of the graphs, it can be concluded that the proposed damage identification method works very well for damage identification purposes.

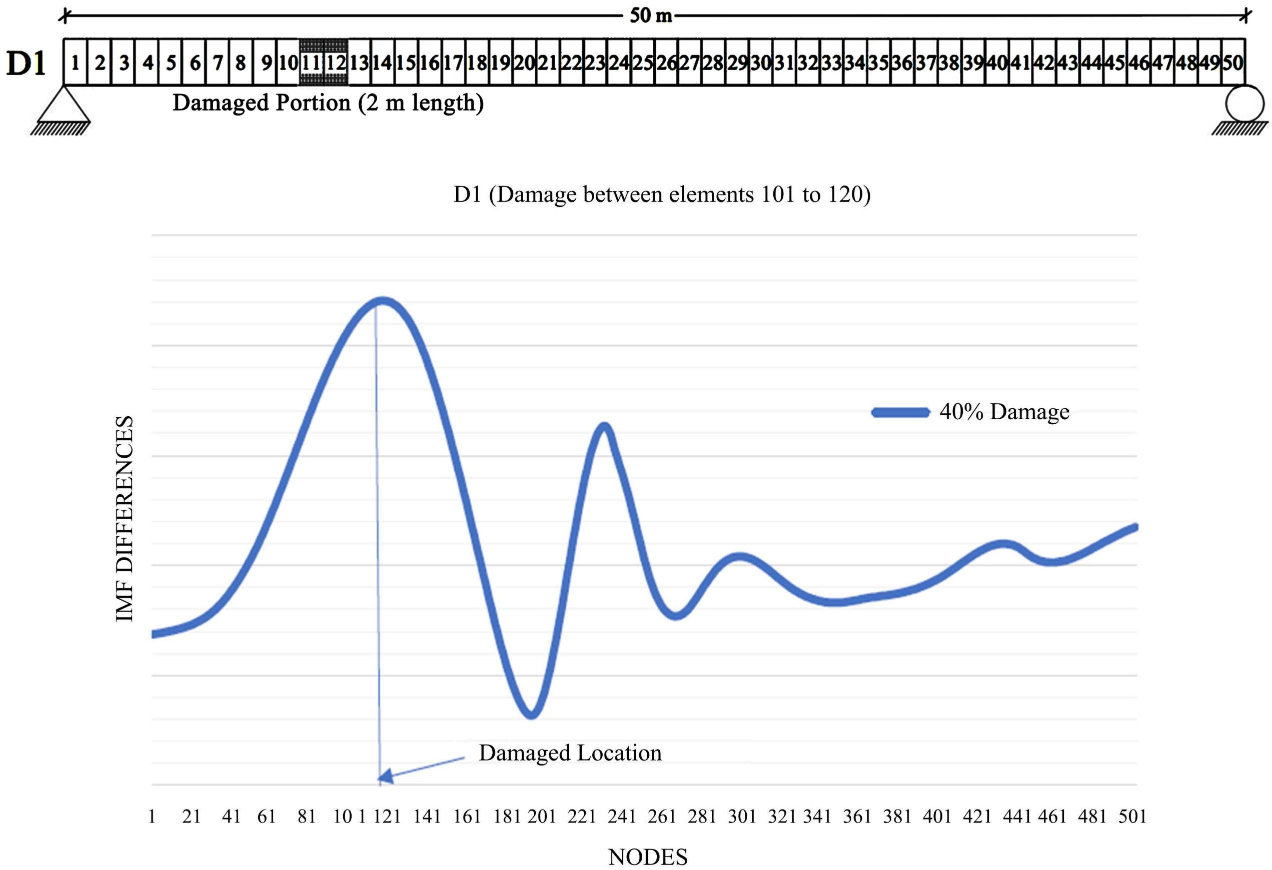

Figure 8. Damage identification for (D1).

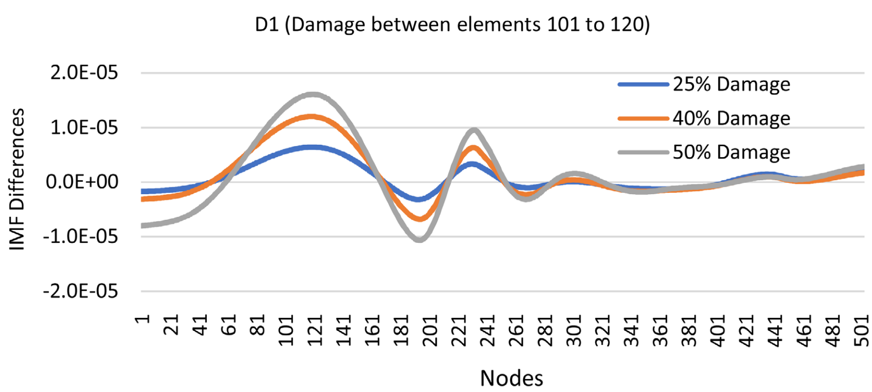

Figure 9. Damage identification for different severity cases (D1).

3.2. Damage Identification for Scenario D2

Scenario of the single-damage case, D2, will be shown in **Figure 10** below and corresponding peak differentiate between the damage positions for damage severity cases of 25%, 40% and 50%. The peaks referring to IMF differences increase due to change in the damage severity. The difference between the speed pseudo-frequency parts of the acceleration signals for the healthy and damaged structures is sensitive to damage.

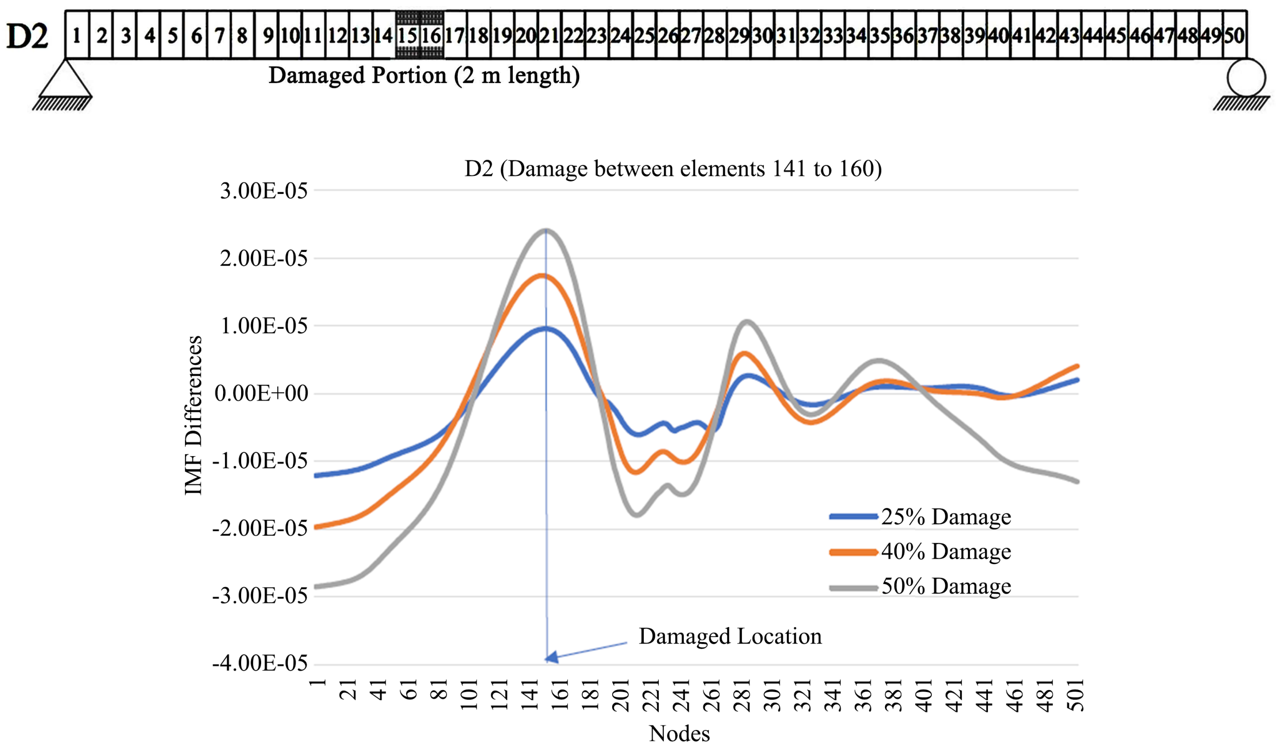

Figure 10. Damage identification for different severity cases (D2).

4. Conclusion

In this study, we have developed a novel method for indirect damage detection based on the rotational displacement response of a vehicle. We applied a computational model to a real-world structure, the Teesta Bridge, and tested the efficacy of the method by examining four diverse damage scenarios, each located at a different point on the bridge and with varying levels of severity. We created a two-dimensional finite element (FE) model of the bridge for the purpose of modeling the interaction between the vehicle and the bridge. Numerical investigations verified that, given appropriate vehicle parameters, the vibration response of the vehicle is effective not only in detecting changes in the bridge due to damage but also in pinpointing the location of the damage and assessing its severity. This study led us to several key findings:

1) The interaction between the vehicle and bridge significantly influences the dynamic response, a topic explored in this paper.

2) The dynamic behavior of a vehicle traversing a bridge can be harnessed to determine the pitching rotation, which in turn can be used to identify bridge damage.

3) The Intrinsic Mode Function (IMF) differences for damage levels of 25%, 40%, and 50% were calculated and graphed alongside the non-damaged IMF. The results showed a clear distinction between damaged and undamaged states.

4) This method was successful in determining the location of the damage on the bridge and in comparing the severity of different instances of damage.

Conflicts of Interest

The authors declare no conflicts of interest regarding the publication of this paper.

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