Rapid Detection of Track Changes from Onboard Data Acquisition Records

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Track stiffness fluctuations serve as early indicators of potential infrastructure issues, posing risks to both passenger safety and service reliability. Traditional monitoring methods like visual inspection and ultrasonic testing fall short in delivering consistent and comprehensive network-wide monitoring, underscoring the demand for robust track stiffness monitoring systems. This study aims to detect track stiffness variations by using dynamic responses obtained from in-service trains. The proposed novel and efficient hybrid signal processing algorithm detects stiffness changes from vertical acceleration records obtained from onboard sensors. The proposed system shows enhanced sensitivity to measurements, is resilient to noise, and has defect localization capabilities. This integrated approach facilitates a comprehensive evaluation of track stiffness changes across various timeframes and frequency ranges. Dynamic response analysis, particularly through the HWHT method, presents a promising avenue for advancing railway track stiffness monitoring. Leveraging real-time data from in-service trains and advanced signal processing techniques, this method enables timely detection of stiffness variations, thereby augmenting operational safety and efficiency within railway systems.</td></tr>
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Table of Contents

List of Figures 4
List of Abbreviations 4
Disclaimer 4
Acknowledgements 4
1 SUMMARY 5
2 BACKGROUND 5
3 OBJECTIVES 6
4 METHODS 7
4.1 Hybrid Wavelet-Hilbert transform (HWHT) 7
4.2 Numerical model 7
5 RESULTS 9
5.1 Detailed steps for a simple case 9
5.2 Evaluation of the proposed method by introducing different cases 11
6 CONCLUSIONS 13
7 FUTURE WORK 13
8 REFERENCES 14

List of Figures

Figure 1: Schematic of auxiliary mass system over track 8
Figure 2: Simulator input and output: (a) track stiffness change; (b) ABA record 9
Figure 3: WPA output: (a) WP coefficients; (b) subset reconstruction 10
Figure 4: HHT output: (a) Analytical signal magnitude; (b) IMF1 Fourier spectrum 10
Figure 5: Hilbert instantaneous energy: (a) Hilbert spectrum; (b) Instantaneous energy 11
Figure 6: Proposed algorithm evaluation: (a) track stiffness changes; (b) Hilbert Spectrums; (c) Instantaneous energy 12

List of Abbreviations

2-DOF	2-Degree-of-Freedom
ABA	Auxiliary-Based Analysis
GPR	Ground Penetrating Radar
HHT	Hilbert-Huang Transform
HWHT	Hybrid Wavelet-Hilbert Transform
WP	Wavelet Packet
WPA	Wavelet Packet Analysis

Disclaimer

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1 SUMMARY

The expansion of the United States railway network emphasizes the critical need for ongoing track stiffness monitoring to maintain safety and operational effectiveness. Track stiffness fluctuations serve as early indicators of potential infrastructure issues, posing risks to both passenger safety and service reliability. However, traditional monitoring methods like visual inspection and ultrasonic testing fall short in delivering consistent and comprehensive network-wide monitoring, underscoring the demand for robust track stiffness monitoring systems. This study aims to detect track stiffness variations by using dynamic responses obtained from operational trains. It proposes that vertical acceleration measurements can efficiently pinpoint stiffness changes, offering faster fault detection than conventional inspection methods. The aim is to establish a comprehensive detection system capable of identifying anomalies based on deviations from historical performance, thereby enabling network-wide monitoring without the need for manual identification of problematic areas. By introducing the Hybrid Wavelet-Hilbert Transform (HWHT) method, the study integrates Wavelet Packet Analysis (WPA) and the Hilbert-Huang Transform (HHT) to enhance sensitivity, noise resilience, and defect localization capabilities. This integrated approach facilitates a comprehensive evaluation of track stiffness changes across various timeframes and frequency ranges. Dynamic response analysis, particularly through the HWHT method, presents a promising avenue for advancing railway track stiffness monitoring. Leveraging real-time data from in-service trains and advanced signal processing techniques, this method enables timely detection of stiffness variations, thereby augmenting operational safety and efficiency within railway systems.

2 BACKGROUND

Given the total length of the railway network in the United States surpassing 250,000 km and still expanding fast, effective monitoring of track stiffness emerges as a critical imperative for ensuring railway safety and efficiency [1]. Variations in track stiffness serve as key indicators of potential defects or deterioration within railway infrastructure [2]. This poses risks to passenger safety and operational reliability [3, 4]. Consequently, the need for comprehensive track stiffness monitoring throughout the railway track life cycle is evident. Current methods lack the capability to offer regular and thorough monitoring across the network, leading to periodic maintenance scheduling. However, this infrequent maintenance approach not only increases unsafe transportation risks but also disrupts railway operations [5]. This emphasizes the importance of implementing effective health monitoring systems. Such systems are vital for optimizing railway system functionality and mitigating risks associated with track stiffness variations.

The most common method for inspecting railway stiffness changes is visual inspection, either through manual operation or image processing [6]. Even though it is costly and time-consuming, it is effective in detecting surface stiffness-related defects, including broken sleepers and missing fasteners. It is not feasible, however, to identify loose fasteners and damaged ballast under sleepers. Ultrasonic testing is another method used for stiffness change inspection [7], which can be easily conducted by a specific inspection vehicle. Ground Penetrating Radar (GPR) is capable of evaluating the ballasted track bed condition, which is similar to the ultrasonic pulse-echo technique by using electromagnetic waves instead of ultrasonic waves [8]. Recent developments in sensing technology [9] and computational power have provided new opportunities to improve railway track monitoring strategies and reduce inspection costs. Vibration-based sensors are commonly used to monitor dynamic behavior, which can indicate defects [10-13]. The installation of vibrational sensors directly on tracks usually provides useful information about their condition, but instrumenting the entire railway network is not feasible and would be extremely expensive [5]. In recent years, several studies have proposed the installation of sensors on a passing train for track health monitoring [12, 14, 15]. In addition to not disrupting normal service, this method provides real-time data about the track condition every time a train passes. Therefore, it can detect track defects early. In addition to being cost-effective instrumentation, this method could be fitted to all trains, eliminating expensive track measurement vehicles.

3 OBJECTIVES

The majority of civil assets in the United States are still monitored by visual inspection, while continuous monitoring has become cost-effective in the manufacturing and aerospace fields. This study aims to detect railway track stiffness loss by using dynamic responses collected from in-service trains. The main hypothesis is that vertical acceleration can be used to infer track stiffness change. Due to the frequent passing of passenger trains over track sections, faults can be detected earlier than with dedicated inspection vehicles, and data-driven approaches can be statistically viable. Most traditional damage detection methods require comparing the dynamic properties of the damaged structure with those of its intact state, which may not always be possible in practice. The aim is to build a broader detection system that defines anomalies as changes in behavior from a historical baseline. Using this historical detection technique, an entire network can be monitored without manually flagging problematic areas.

4 METHODS

4.1 Hybrid Wavelet-Hilbert transform (HWHT)

This method leverages the complementary strengths of Wavelet Packet Analysis (WPA), which excels in decomposing signals into different frequency components, and the Hilbert-Huang Transform (HHT), which specializes in analyzing nonlinear and non-stationary signals. By integrating these two techniques, the hybrid method offers several advantages, including enhanced sensitivity to stiffness variations, robustness to noise, and accurate localization of defects. Furthermore, the multi-scale analysis capabilities of wavelet packet analysis and the adaptability of HHT enable the hybrid method to provide a comprehensive assessment of track stiffness changes across different time scales and frequency bands. In this study, we present an overview of the hybrid method for track stiffness change detection, discussing its underlying principles, advantages, and potential applications in railway maintenance and safety. We also review recent developments and case studies showcasing the effectiveness of this method in real-world railway environments. Through this exploration, we aim to highlight the significance of the hybrid method as a valuable tool for enhancing railway infrastructure monitoring and maintenance, ultimately contributing to the safety and reliability of railway transportation systems.

4.2 Numerical model

In this study, we developed a comprehensive numerical model using a 2-degree-of-freedom (2-DOF) auxiliary mass system to simulate onboard track stiffness change detection. This model incorporates a spring-dashpot system to represent the Hertzian contact between the wheel and rail, with the contact point precisely mapped based on our previous studies. Additionally, a secondary spring-dashpot connection simulates the primary suspension system, which is crucial for capturing high-frequency interactions between the wheel and rail. The top mass in this configuration represents the combined mass of the bogie and car body, allowing the model to maintain computational efficiency while accurately reflecting real-world dynamics.

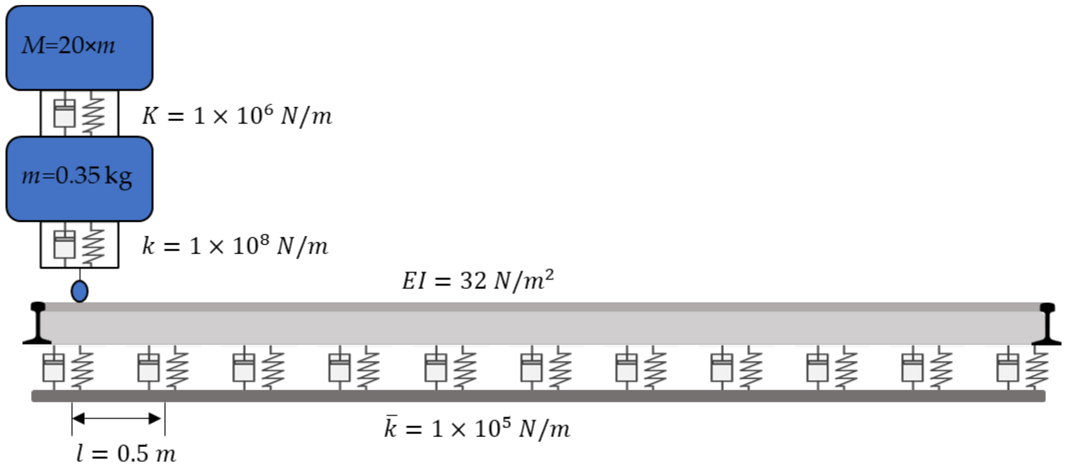

Figure 1: Schematic of auxiliary mass system over track

The rail track is modeled as a Timoshenko beam, which accounts for shear deformation and rotational bending effects, providing a detailed and realistic representation of the rail's behavior. To simulate the support conditions of the rail track, we use a beam over multiple layers of distributed spring-damper elements. The stiffness of these spring elements is dynamically adjusted to reflect varying track conditions, such as loose fasteners or damaged ballast. For instance, the stiffness is reduced if a fastener is loose or ballast is compromised and is considered zero if a fastener is missing, or the sleeper is unsupported due to poor ballast condition. This approach enables the model to respond accurately to real-time changes in track conditions.

The distributed spring-damper elements are placed at intervals corresponding to the sleeper spacing, which is critical for accurately representing the track's support conditions. This configuration allows for a detailed evaluation of the track's structural integrity under different scenarios. The primary goal of this model is to assess the feasibility and effectiveness of ABA in detecting real-time changes in track stiffness. By simplifying the complex interactions between the wheel and rail into a manageable computational model, we ensure cost-effectiveness while maintaining the necessary accuracy to identify critical changes in track conditions.

This numerical model serves as a robust tool for predicting rail track performance and identifying potential issues such as loose fasteners, damaged ballast, or unsupported sleepers.

5 RESULTS

5.1 Detailed steps for a simple case

In this study, track stiffness change is represented by a step function with a pronounced jump in the middle of the track, as illustrated in Figure 1. The dynamic response of the auxiliary mass system is evaluated over the entire track length, and the Auxiliary-Based Analysis (ABA) record is shown in Figure 2. The dynamic system evaluation employs a 5-millisecond time step, resulting in a sampling frequency of 200 Hz. This frequency selection allows us to analyze the ABA record for frequencies below 100 Hz, with a specific focus on identifying changes within the low-frequency range, particularly those less than 25 Hz.

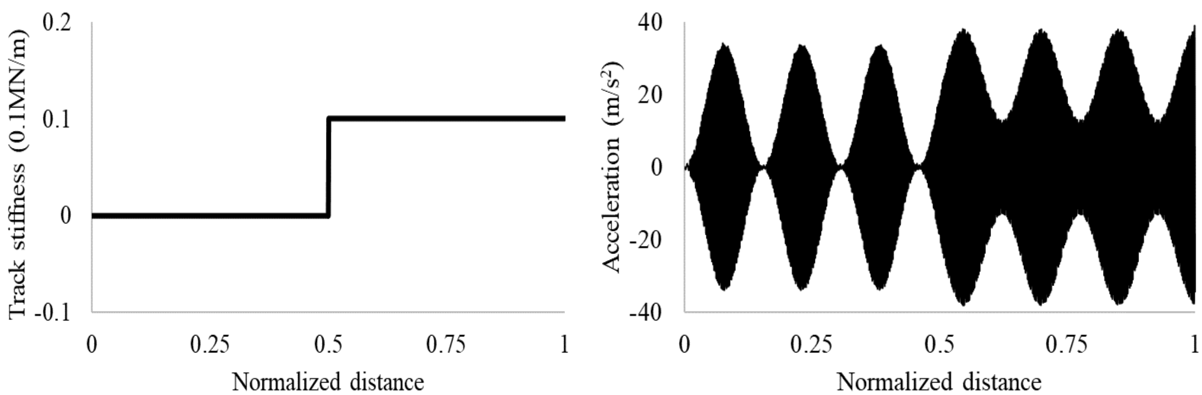

Figure 2: Simulator input and output: (a) track stiffness change; (b) ABA record

To achieve this, the ABA record is decomposed into four subsets, each covering specific frequency bands up to 100 Hz. The subset representing frequencies from 0 to 25 Hz is selected for further analysis. The corresponding Wavelet Packet (WP) coefficients and the subset are depicted in Figure 3. This selected subset is then processed using the Hilbert-Huang Transform (HHT) algorithm to evaluate the complex signal and its corresponding instantaneous energy.

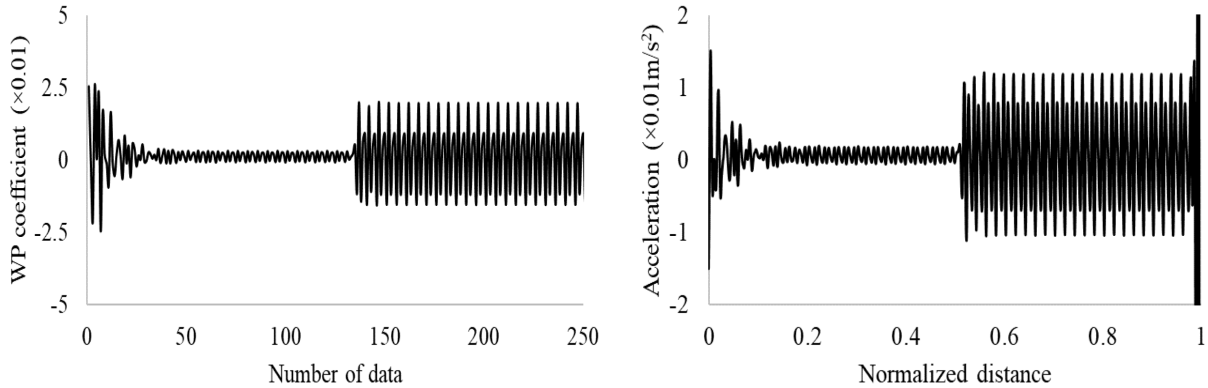

Figure 3: WPA output: (a) WP coefficients; (b) subset reconstruction

Figure 4a shows the magnitude of the analytical signal using the HHT method. Notably, the zoomed-in section reveals a distinct shift at the midpoint of the path, indicating the distribution of track stiffness change introduced in this section. The frequency component of the signal, presented in Figure 4b, shows that the predominant frequency is 20 Hz.

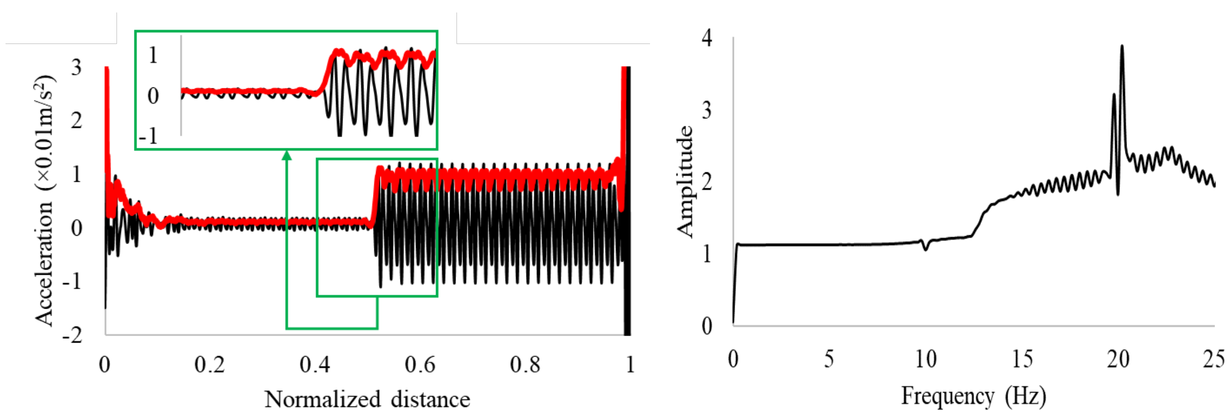

Figure 4: HHT output: (a) Analytical signal magnitude; (b) IMF1 Fourier spectrum

The Hilbert spectrum, displayed in Figure 5, evaluates the instantaneous energy of the analytical signal within a time-frequency framework. The spectrum indicates that the energy fluctuation around the 20 Hz frequency, noted earlier, begins at the midpoint and continues to the end of the track. This fluctuation behavior remains consistent throughout. Additionally, the instantaneous energy of the analytical signal is found to be negligible. Figure 5b plots the instantaneous energy amplitude, where the red graph represents the rolling average of instantaneous energy fluctuations.

There is a strong correlation between this graph and the introduced stiffness change graph, suggesting that with a known transfer function between instantaneous energy and track stiffness change, this method holds promise for onboard track stiffness change detection and measurement through ABA records.

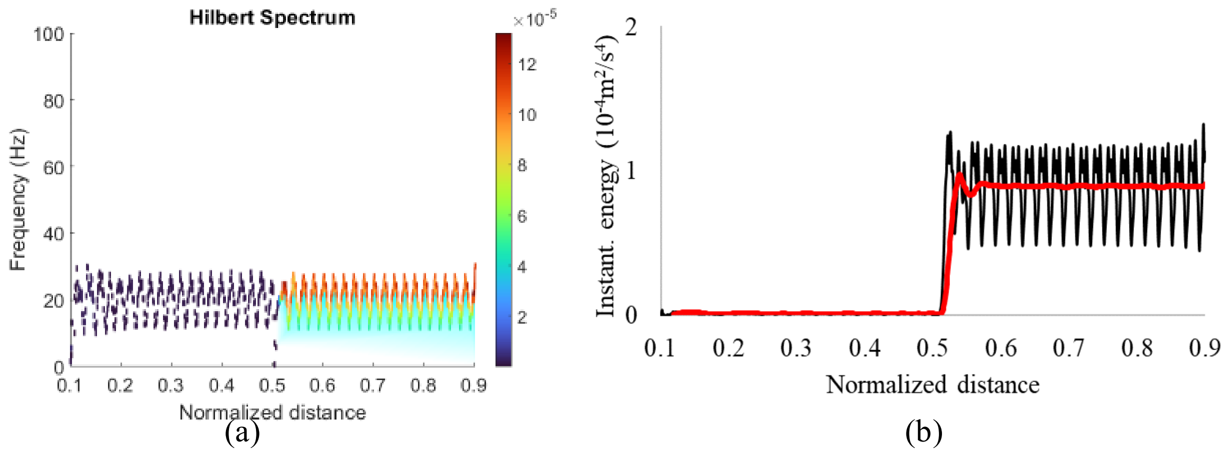

Figure 5: Hilbert instantaneous energy: (a) Hilbert spectrum; (b) Instantaneous energy

To further validate the method, the study evaluates the approach for three additional cases of track stiffness change trends. These cases will help demonstrate the robustness and reliability of the proposed system in various track conditions, reinforcing its potential for real-time track monitoring and maintenance applications.

5.2 Evaluation of the proposed method by introducing different cases

In this section, the effectiveness of the proposed algorithm for detecting track stiffness changes is evaluated by introducing three distinct track stiffness change trends, as depicted in Figure 6a. The algorithm's performance is assessed by applying it to these three predefined stiffness change trends. The results, shown in Figures 6b and 6c, clearly demonstrate the algorithm's capability to accurately capture and identify the changes in track stiffness. For each trend, the dynamic response of the auxiliary mass system is analyzed, and the corresponding ABA records are processed to detect shifts in track stiffness. In Figure 6b, the algorithm's response to each trend is plotted, showcasing its sensitivity to various types of stiffness changes. The results indicate that the algorithm successfully identifies both abrupt and gradual changes in stiffness, validating its robustness across different scenarios. Additionally, Figure 6c provides a detailed comparison between the detected stiffness changes and the actual trends introduced in the simulation. This comparison further illustrates the algorithm's precision in tracking stiffness variations, with a high degree of correlation between the detected changes and the predefined trends. The successful detection of these changes across multiple cases underscores the algorithm's reliability and accuracy.

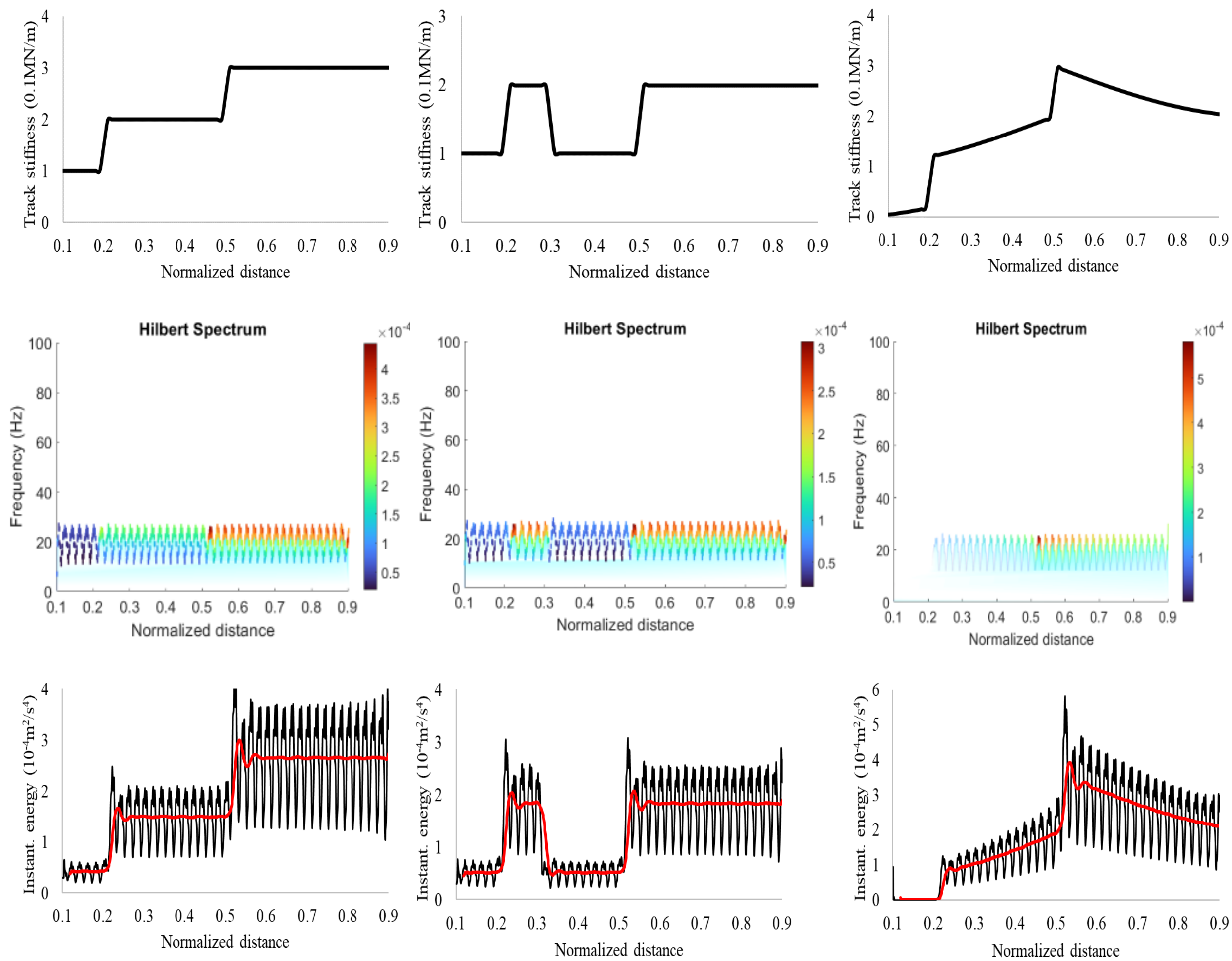

Figure 6: Proposed algorithm evaluation: (a) track stiffness changes; (b) Hilbert Spectrums; (c) Instantaneous energy

6 CONCLUSIONS

In this study, we developed and evaluated a numerical model for onboard track stiffness change detection using a 2-degree-of-freedom auxiliary mass system. The model simulates the dynamic interaction between the wheel and rail, incorporating key elements such as Hertzian contact, primary suspension dynamics, and track support conditions represented by distributed spring-damper elements. We employed the ABA method to monitor and analyze changes in track stiffness. The model was tested against various predefined track stiffness change trends to assess its effectiveness and accuracy in detecting these changes.:

- By decomposing the ABA record into specific frequency bands and focusing on the 0-25 Hz range, the model successfully identifies changes in track stiffness. The Hilbert-Huang Transform (HHT) method enhances the analysis by providing detailed insights into the instantaneous energy and frequency components of the signal.
- The algorithm demonstrated a high sensitivity to different track stiffness change trends, including abrupt, gradual, and periodic variations. The results consistently showed a strong correlation between detected changes and the actual predefined trends, validating the model's robustness.

The promising results suggest that the proposed method can be a valuable tool for railway operators, contributing to safer and more efficient railway operations.

7 FUTURE WORK

Future work will focus on further validating the method under different track conditions, evaluating change indices to classify different stiffness changes based on their severity, conducting noise robustness studies, examining the effects of train speed on detection accuracy, and exploring the integration of this method into existing railway monitoring systems. This continued research aims to refine the method and ensure its practical applicability in diverse and real-world railway environments.

8 REFERENCES

1. Naseri, R., et al. *A Hybrid Rail Surface Spot Irregularities (Rssi) Detection Algorithm Based on Onboard Measurements*. in *ASME/IEEE Joint Rail Conference*. 2024. American Society of Mechanical Engineers
2. Wang, L., Y. Zhang, and S.T. Lie, *Detection of damaged supports under railway track based on frequency shift.* Journal of Sound and Vibration, 2017. **392**: p. 142-153, https://doi.org/10.1016/j.jsv.2016.11.018.
3. Naseri, R. and S. Mohammadzadeh, *Nonlinear Train-Track-Bridge Interaction with Unsupported Sleeper Group.* International Journal of Railway Research, 2020. **7**(1): p. 11-28, https://doi.org/10.22068/IJRARE.7.1.11.
4. Naseri, R., S. Mohammadzadeh, and D.C. Rizos, *Rail surface spot irregularity effects in vehicle-track interaction simulations of train-track-bridge interaction.* Journal of Vibration and Control, 2024: p. 10775463241232024, 10.1177/10775463241232024.
5. Naseri, R., B.L. Gedney, and D.C. Rizos, *Hybrid rail squat detection algorithm using axle box acceleration.* To be submitted, 2024
6. Malekjafarian, A., et al., *Railway track loss-of-stiffness detection using bogie filtered displacement data measured on a passing train.* Infrastructures, 2021. **6**(6): p. 93
7. Loveday, P.W., C.S. Long, and D.A. Ramatlo, *Ultrasonic guided wave monitoring of an operational rail track.* Structural Health Monitoring, 2020. **19**(6): p. 1666-1684
8. Wang, S., et al., *State-of-the-art review of ground penetrating radar (GPR) applications for railway ballast inspection.* Sensors, 2022. **22**(7): p. 2450
9. Pannese, E.M., et al., *Bridge transition monitoring: Interpretation of track defects using digital image correlation and distributed fiber optic strain sensing.* Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 2020. **234**(6): p. 616-637
10. Aied, H., A. González, and D. Cantero, *Identification of sudden stiffness changes in the acceleration response of a bridge to moving loads using ensemble empirical mode decomposition.* Mechanical Systems and Signal Processing, 2016. **66-67**: p. 314-338, https://doi.org/10.1016/j.ymssp.2015.05.027.
11. Lederman, G., et al., *Track-monitoring from the dynamic response of an operational train.* Mechanical Systems and Signal Processing, 2017. **87**: p. 1-16, https://doi.org/10.1016/j.ymssp.2016.06.041.
12. Quirke, P., et al., *Drive-by detection of railway track stiffness variation using in-service vehicles.* Proceedings of the Institution of Mechanical Engineers, Part F: Journal of Rail and Rapid Transit, 2017. **231**(4): p. 498-514
13. Shen, C., R. Dollevoet, and Z. Li, *Fast and robust identification of railway track stiffness from simple field measurement.* Mechanical Systems and Signal Processing, 2021. **152**: p. 107431, https://doi.org/10.1016/j.ymssp.2020.107431.
14. Sun, X., et al., *On-board detection of longitudinal track irregularity via axle box acceleration in HSR.* IEEE Access, 2021. **9**: p. 14025-14037
15. Traquinho, N., et al., *Damage Identification for Railway Tracks Using Onboard Monitoring Systems in In-Service Vehicles and Data Science.* Machines, 2023. **11**(10): p. 981