Structural Health Monitoring of High-speed Railways Using Ultrasonic Guided Waves

YANFENG SHEN, JUNFANG WANG and YI-QING NI

ABSTRACT

This paper presents a damage detection strategy for high-speed railways using piezoelectric active sensors. Multimodal ultrasonic guided waves generated by a piezoelectric transmitter propagate along the rail track, undergo dispersion, interact with the damage zone, and are finally picked up by the sensors. First, numerical investigations are carried out to understand the guided wave features and their interaction mechanism with typical damage scenarios in the railways. The modal analysis of a finite element scheme with Bloch-Floquet condition is conducted to obtain the dispersion characteristics and the mode shapes of the rail track guided waves. Optimum wave generation location and frequency were explored using a small-size local coupled field finite element model. Further, a Local Interaction Simulation Approach (LISA) model was developed to achieve efficient simulation of elastic wave propagation in railway structures. The LISA procedure was coded using the Compute Unified Device Architecture (CUDA), which enables the highly parallelized computing on powerful Graphics Processing Units (GPUs). This transient dynamic analysis reveals the influence of rail track features and damage signature on the sensing signals. Finally, full-scale experiments on a BS 90A rail track with embedded piezoelectric sensors are carried out to compare with the numerical investigations. This study shows that the active sensing system possess promising potential for the in-situ health monitoring of railway structures.

INTRODUCTION

High-speed railways are prone to develop various types of damage, such as cracks and corrosion, during their service. The prompt detection and in-situ monitoring of damage zones is becoming a critical demand to ensure the operation safety of railway

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systems [1]. Guided waves have been identified as promising inspection tools for Structural Health Monitoring (SHM). They can propagate long distances without much energy loss, enabling large-scale structural inspections. Piezoelectric transducers have been widely investigated as enablers to generate and receive ultrasonic guided waves. They can be permanently installed on the host structures and achieve real-time structural sensing.

However, guided wave propagation in rail tracks is rather complex. The difficulty of utilizing guided waves for rail track inspection arises from their multi-modal and dispersive nature. Thus, it is important to obtain an in-depth understanding of the guided wave phenomena in such complex waveguides. Semi-Analytical Finite Element (SAFE) method has been developed, which would provide the dispersion relations and mode shapes of guided waves in complex waveguides [2]. Nevertheless, SAFE method is not suitable for solving transient dynamic wave damage interactions, which is especially true for localized nonlinear problems. On the other hand, Finite Element Method (FEM) is widely used for simulating elastodynamic wave phenomena, but the requirement imposed on the dense discretization on both temporal and spatial variables usually makes the target problem computationally inhibitive. As an effort for developing more efficient numerical tools for elastic wave simulation, Delsanto et al. proposed a technique called the Local Interaction Simulation Approach (LISA) using explicit finite difference formulations [3]. Lee and Staszewski applied LISA to study wave propagation in isotropic plates and their interaction with damage with a two-dimensional model [4]. Packo et al. parallelized LISA using Compute Unified Device Architecture (CUDA) running on Graphical Processing Unit (GPU) [5]. Nadella and Cesnik extended the 3-D LISA to model laminate composites with arbitrary lamination angles [6]. Recently, Shen and Cesnik added viscous damping and contact dynamics modeling capability into LISA for the simulation of damped guided wave propagation and nonlinear interactions between guided waves and fatigue cracks [7, 8].

This study aims to investigate the guided wave active sensing technique for the in-situ monitoring of rail tracks. First, the guided wave features are computed using a Bloch-Floquet FEM approach. Then, the guided wave excitability is studied via a local FEM with absorbing boundaries. Further, the active sensing procedure involving guided wave generation, propagation, interaction with damage, and reception is modeled with LISA. Experiments on a full-scale BS 90A rail track is carried out to verify the simulation results.

GUIDED WAVE CHARACTERISTICS IN RAILWAYS

Finite element method with Bloch-Floquet boundary conditions has been widely used to model dynamic response of periodic structures. Large scale waveguides have been treated as the connection of subsections of periodic components (unit cells) for the solution of dispersion curves and mode shapes [9].

Figure 1 presents the unit finite element cell with Bloch-Floquet boundary condition as well as the spatial discretization of a BS 90A rail track cross section. The Bloch-Floquet boundary condition imposes displacement constrains, implying a $e^{i\xi_x a_x}$ phase delay between the unit cell boundaries. ξ_x represents the wavenumber in x

direction, defining a corresponding wavelength at the angular frequency ω. a_x is the unit cell dimension in the wave propagation direction which is assumed to be x direction along the rail track. The unit cell thickness usually takes a very small value, 0.1 mm for the current analysis, to accurately capture short wavelength ultrasonics waves. The solving scheme sweeps through the wavenumber domain. At each wavenumber, corresponding to a certain wavelength, the only unknown terms in the dynamic equation system are the frequencies. Thus, the target problem retrieves to the conventional modal analysis, where the eigenvalues are the frequencies of the wave modes possessing the same defined wavelength and the eigenvectors represent their mode shapes. The physical interpretation of the solving mechanism can be perceived from the nature of guided waves: cross-sectional mechanical resonance propagating in the normal direction.

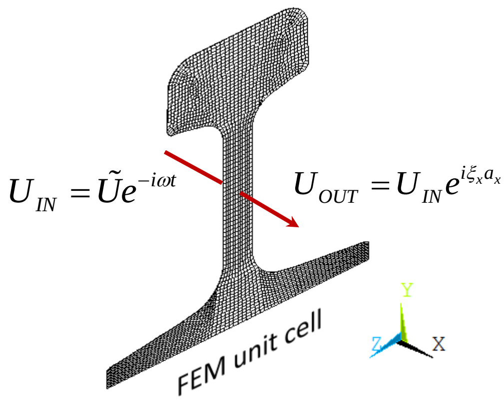

Figure 1: Unit finite element cell with Bloch-Floquet boundary condition for the computation of guided wave dispersion and mode shapes.

Figure 2 shows the dispersion relations obtained from the Bloch-Floquet FEM. The multimodal, dispersive nature of guided wave is quite obviously illustrated. It can be noticed that excessively large number of wave modes exist across the ultrasonic frequency range. Even at critically low frequency values, large number of fundamental modes are present. Such effect is caused by the size and complex geometric features of the rail track structure. The wave speeds change across the frequency, displaying the dispersive characteristics of guided waves in the rail track. It is noted that at high frequency range, the guided wave speeds converge to the surface Rayleigh waves.

Figure 3 plots the featured guided wave modes and categorized with respect to the dominant motion locations on the rail track cross-sectional area. The first column presents the rail head modes, where the wave energy mainly concentrates on the rail head. The second column shows the rail web modes, where the dominant wave motion happens at the rail web. The third column demonstrates the rail foot modes, where the wave dynamics is barely noticeable at both the rail head and rail web. The fourth column, in general, shows a more common situation, the comprehensive modes, where the entire rail cross section vibrates during the wave propagation. The mode shape profiles are directly related to the sensitivity of the corresponding wave mode to different damage locations. For example, the rail foot modes possess much higher interrogating sensitivity to damage zones locating on the rail foot, rather than damage zones on the rail head. Conversely, to monitor the rail foot damage, the rail foot modes are more suitable to perform the SHM task.

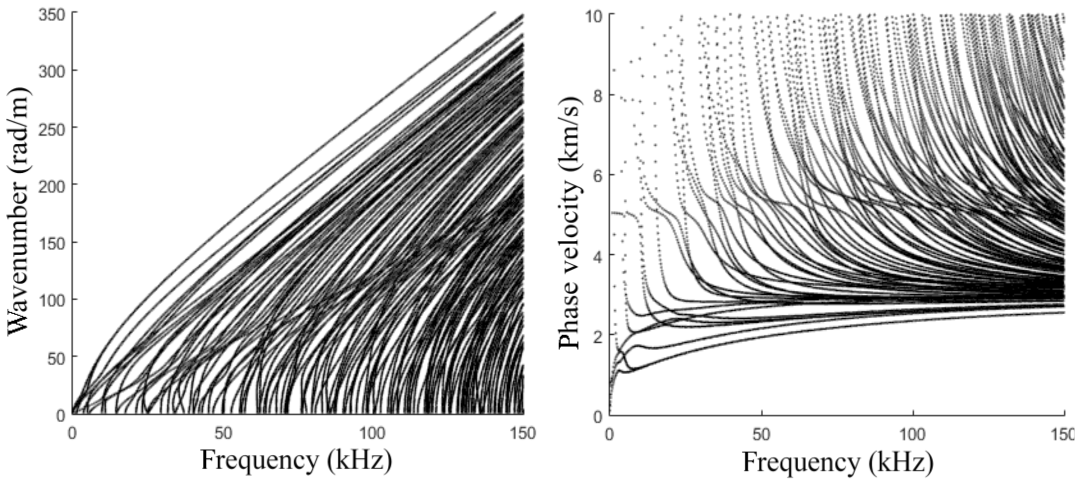

Figure 2: Guided wave dispersion curve results for the BS 90A rail track: frequency-wavenumber representation (left); frequency-phase velocity plot (right).

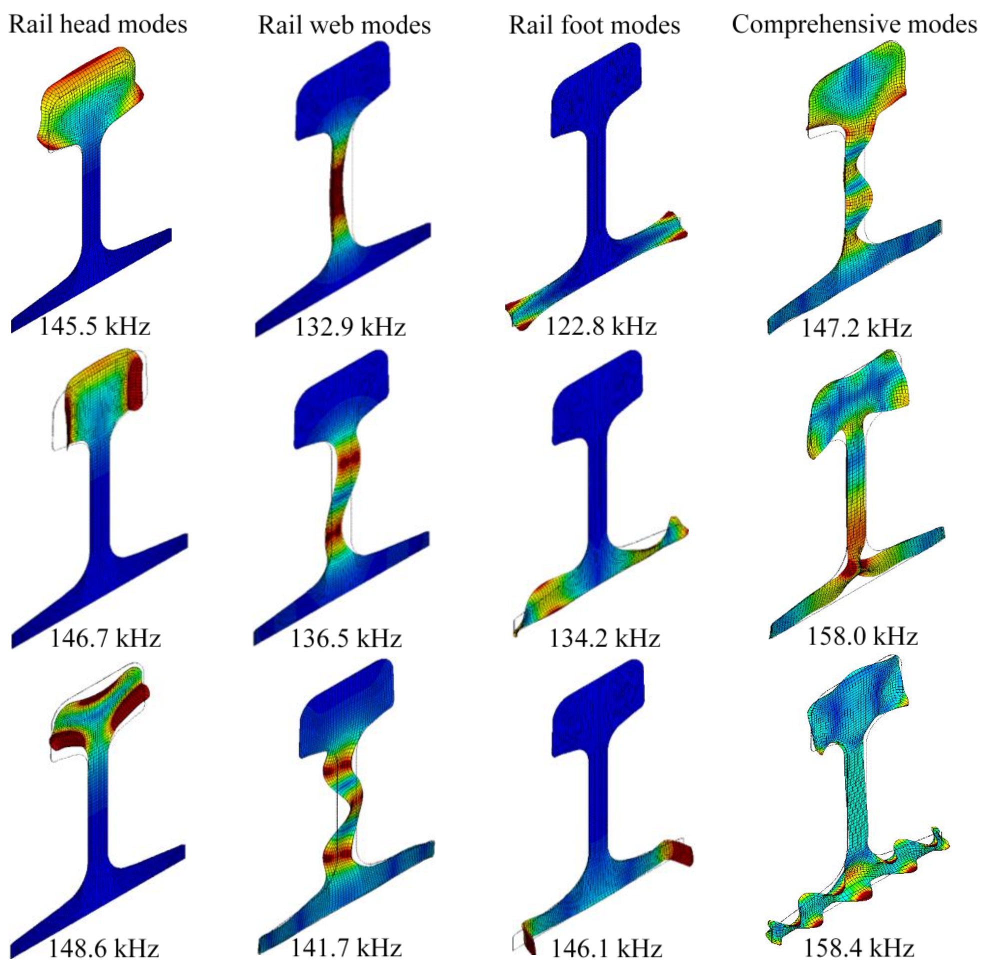

Figure 3: Representative guided wave mode shapes in the rail track categorized by motion characteristics: rail head modes (first column); rail web modes (second column); rail foot modes (third column); comprehensive modes (fourth column).

MODELING OF GUIDED WAVE ACTIVE SENSING FOR RAIL TRACKS

Built upon the comprehensive understanding of the guided wave features in the rail tracks, it is apparent that damage at different rail cross section zones can be effectively detected if tailored localized wave modes can be excited and used for the interrogation purpose. In this section, the guided wave generation, propagation, interaction with damage, and reception are modeled by a transient dynamic LISA model. Guided wave excitability is captured via a small-size coupled field local FEM and then input into the global LISA solution.

Guided Wave Excitability in Rail Tracks

Figure 4 shows the small-size local FEM used to obtain the guided wave excitability solution in the rail track, generated by a 1-mm thick, 10-mm long, 8-mm wide piezoelectric wafer. The transducer was bonded on the rail foot corner side. The rationale for such an installation practice aims to excite localized rail foot guided wave mode depicted in Figure 3. Extended region of Absorbing Layers with Increasing Damping (ALID) was implemented at both ends of the rail track to eliminate the boundary reflections as well as to minimize the model size. Thus, the computation of wave generation in infinitely long rail tracks can be achieved with a finite size model. Coupled field elements are used to model the piezo transducer. Harmonic solution is performed, providing wave generation information across the entire frequency range of interest. Frequency domain convolution with excitation profiles and forward and inverse Fourier transforms are performed to import the solution into the transient LISA formulation. It can be noticed that below 200 kHz, nearly all the excited wave energy is confined within the rail foot. However, beyond 200 kHz, wave motion into the rail web and head sections is found, indicating that complex wave modes would be excited. Tuning experiments and local FEM agree with each other, both identifying 140 kHz being the sweet point for effective generation of rail foot guided wave mode.

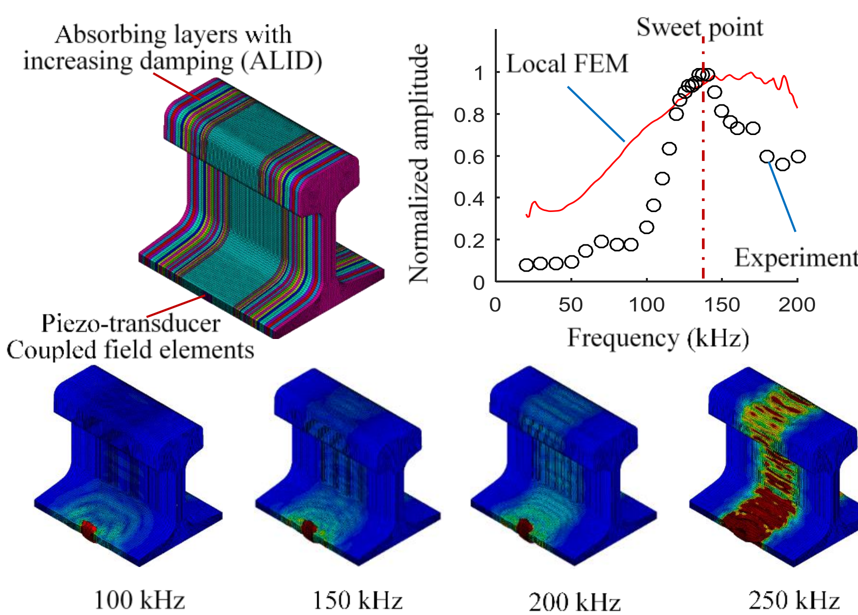

Figure 4: Local FEM solution of guided wave excitability by a piezo-transducer installed on the rail foot.

LISA Model of Guided Wave SHM for Rail Tracks

Figure 5 presents the LISA model for guided wave propagation and interaction with a notch in a BS 90A rail track. A 140 kHz 5-cycle tone burst is used for wave generation. The ultrasonic waves propagate along the rail track, interact with the notch, and are finally picked up at the sensing location. Absorbing Layers with Increasing Damping (ALID) is used on both ends of the model to eliminate boundary reflections. A 1-mm mesh size is adopted for the cross-sectional area, while a 2-mm mesh sized is deployed for the track direction. The time step according to the Courant–Friedrichs–Lewy (CFL) condition is 114.22 ns, which corresponds to a CFL number of 0.99. Figure 5 shows that the adopted mesh grid can capture the complex geometric details of the rail track. The LISA algorithm was implemented using CUDA technology and executed in parallel on GPUs (NVIDIA GeForce Titan X with 3072 CUDA cores). Although the entire model reached 8,968,401 DOFs, the GPU implementation and parallel computation allows remarkable modeling efficiency.

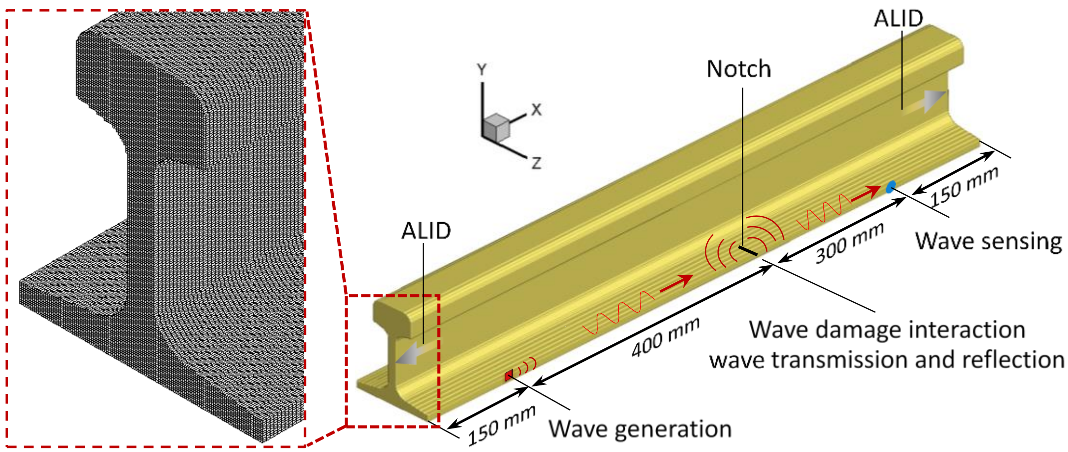

Figure 5: LISA model for guided wave propagation and interaction with a notch in a BS 90A rail track.

EXPERIMENTAL INVESTIGATION AND MODEL VALIDATION

Pitch-catch and pulse-echo active sensing experiments were carried out on a BS 90A rail track to demonstrate the ultrasonic guided wave SHM capability as well as to validate the numerical model for wave propagation in complex rail track structures.

Experimental Setup

Figure 6 demonstrates the experimental setup for rail way active sensing. Guided waves generated by the transmitter propagate along the rail track and interact with a 10-mm deep notch machined by a thin emery cutter. The waves would undergo transmission and reflection at the damage site. The transmitter and receiver 1 work in a pulse-echo mode, detecting reflections from the damage, while the transmitter and receiver 2 work in a pitch-catch mode, capturing the transmitted waves. Agilent 33220A function generator and Tektronix TDS2024C oscilloscope are used to generate the interrogating waves and record the active sensing signals.

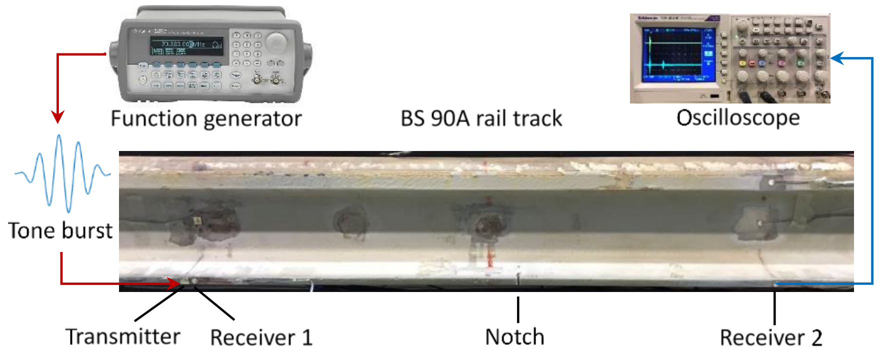

Figure 6: Experimental setup for pitch-catch and pulse-echo active sensing.

Pitch-catch and Pulse-echo Active Sensing Case Study

Figure 7 presents the LISA simulation results with snapshots showing wave generation, localized rail foot guided wave propagation, interaction with the notch, transmission, and reflection. It should be noted that dominant wave energy propagate in the rail track as the localized rail foot mode through careful tuning of transducer parameters and the excitation frequency. For the pristine case, no echo is found in the sensing signal of receiver 1, and large amplitude is found in the receiver 2 pitch-catch signal. When damage appears, obvious echo signal can be notice in the pulse-echo mode, and the transmitted energy captured by receiver 2 drops noticeably. Note the active sensing signal from both experiments (black lines) and LISA simulation (red lines) agree well with each other, demonstrating LISA's high quality and prowess in modeling wave motion in complex waveguides.

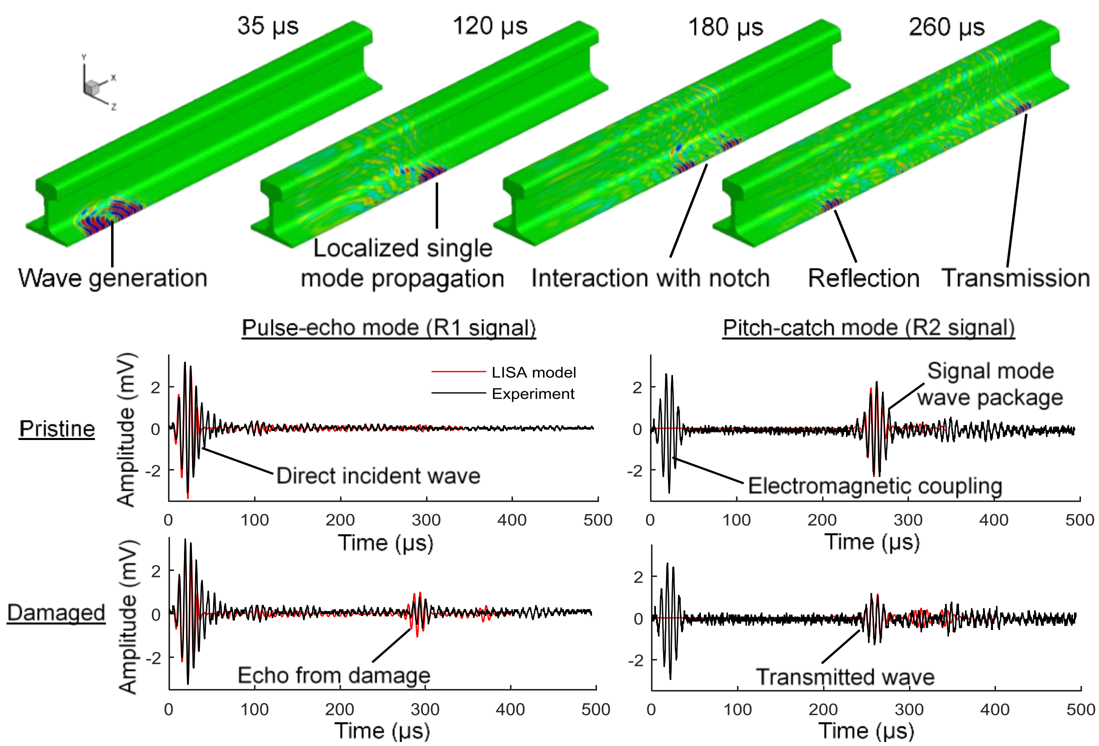

Figure 7: LISA simulation results and comparison with experimental measurements.

CONCLUDING REMARKS

This paper presented the in-situ damage detection technique for rail tracks using ultrasonic guided waves. A Bloch-Floquet FEM procedure was deployed to obtain the multimodal dispersion information of rails. A local FEM and LISA model were utilized to study the guided wave generation, propagation, and interaction with a notch in a BS 90A rail track. Pitch-catch and pulse-echo active sensing experiments were conducted for model validation. The numerical simulation results agreed well with experimental data, demonstrating LISA's high quality and prowess in modeling of wave propagation in complex structures. The guided wave active sensing technique is promising for practical applications for the health monitoring railway infrastructures.

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