COVER SHEET

Title: In-situ Fatigue Damage Detection for Railway Structures Using Nonlinear Ultrasonic Guided Waves

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ABSTRACT

This paper presents a damage detection strategy for rail tracks by taking advantage of the nonlinear interactions between guided waves and fatigue cracks. A Local Interaction Simulation Approach (LISA) was developed to achieve efficient simulation of ultrasonic guided wave propagation in railway structures. The stick-slip contact dynamics at the fatigue cracks was integrated into the LISA model using the penalty method and Coulomb friction law. The LISA procedure was coded with the Compute Unified Device Architecture (CUDA), which enables the highly parallelized supercomputing on powerful Graphics Processing Units (GPUs). Guided waves generated at the transmission location propagate along the rail track, interact with the fatigue crack, carry the Contact Acoustic Nonlinearity (CAN) with them, and are finally picked up at the sensing location. Various fatigue crack size cases were simulated to investigate the change of nonlinear spectrum characteristics from the growing damage severity. A damage index was developed based on the nonlinear ultrasonic energy proportion in the sensing signals to monitor the existence and severity of fatigue cracks. This study shows that the nonlinear ultrasonic techniques possess promising potential for the in-situ health monitoring of railway structures.

INTRODUCTION

Numerous railway structural components are susceptible to fatigue damage. The prompt detection and in-situ monitoring of fatigue zones is becoming a critical demand to ensure the operation safety of high-speed railway systems [1]. Guided waves are promising interrogation tools for Structural Health Monitoring (SHM). They can propagate long distances without much energy loss, enabling large-scale structural inspections.

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Unlike conventional linear ultrasonic techniques which are only sensitive to gross defects, nonlinear ultrasonic techniques further facilitates guided waves with remarkable sensitivity to incipient fatigue damage from the distinctive nonlinear response features such as the higher harmonic generation, sub-harmonic generation, side-band effects, and DC response.

However, guided wave propagation in railway infrastructures, such as the rail tracks, is rather complex. The difficulty of utilizing guided waves for rail track inspection arises from the multi-modal and dispersive nature of guided waves. 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 [3]. 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 [4, 5, 6]. Lee and Staszewski applied LISA to study wave propagation in isotropic plates and their interaction with damage with a two-dimensional model [7]. Sundararaman and Adams extended LISA to three-dimensional problems in isotropic and unidirectional orthotropic plates [8]. Packo et al. parallelized LISA using Compute Unified Device Architecture (CUDA) running on Graphical Processing Unit (GPU) [9]. Nadella and Cesnik extended the 3-D LISA to model laminate composites with arbitrary lamination angles [10].

This study aims to investigate the nonlinear guided wave technique for the in-situ monitoring of rail tracks from a numerical modeling perspective. First, LISA fundamentals are introduced including the inclusion of contact nonlinearity. Then, the guided wave propagation and interaction with fatigue cracks in rail tracks are modeled. Case studies for cracks of various sizes are conducted. Finally, a damage index based on the nonlinear energy proportion of the sensing signals is given to evaluate the fatigue damage severity.

LOCAL INTERACTION SIMULATION APPRAOCH FOR EFFICIENT MODELING OF GUIDED WAVE PROPAGATION

LISA is a finite-difference based numerical method. It approximates the partial differential elastodynamic wave equations with finite difference quotients in the discretized temporal and spatial domains. The coefficients in LISA iterative equations (IEs) depend only on the local physical material properties. The Sharp Interface Model (SIM) enforces the stress and displacement continuity between the neighboring computational cells and nodes. Therefore, changes of material properties in the cells surrounding a computational node can be captured through these coefficients, i.e., LISA can model elastic waves in heterogeneous medium. The final iterative equations determine the displacements of a certain node at current time step based on the displacements of its eighteen neighboring nodes at previous two time steps.

Modeling Structures with Complex Geometries

Toward the modeling of waveguides with complex structural features, one obstacle is the generation of the computational grid and the allocation of material properties to the cells. The LISA IEs require the identification of eighteen neighboring nodes and the material properties in the eight surrounding cells to each target node. In this study, commercial preprocessor in ANSYS is utilized to construct the structure geometry, discretize the model, and assign material properties to each cell. Since the resulting connectivity of nodes and elements follows the convention of FEM, it needs to be converted to the connectivity of LISA, where the eighteen neighboring nodes of each computational point can be identified and all the material properties of its eight surrounding cells can be obtained. A model converter was coded using CUDA to realize such connectivity conversion, after which the eighteen neighboring nodes and eight material properties surrounding each computational point are identified.

Adding Contact Acoustic Nonlinearity into LISA

A penalty method is deployed to introduce contact dynamics into LISA. Penalty method has been adopted as one of the primary approaches to simulate contact problems in FEM. It approximates a constrained problem by an unconstrained one whose solution ideally converges to the solution of the original constrained problem. Its convergence is achieved by punishing the violation of these constrains. For contact analysis, the impenetrability condition in contact continuum mechanics is weakened, which means a small amount of penetration is allowed to enable the mathematical formulation. This penetration can be easily identified as the measurement of violation against the impenetrability condition and is penalized by introducing a contact stiffness that tends to minimize this violation. When an appropriate contact stiffness is reached, the amount of penetration approaches zero, which makes the numerical solution converges towards the physical contact phenomena.

To satisfy the alternating boundary condition between free and constrained situations during crack surface clapping, special treatment of the computational grid is needed. In this study, a discontinuous mesh is used to model the crack surfaces. During the model conversion procedure, three additional steps are taken to prepare the LISA computational grid for the contact analysis, including contact pair recognition, normal direction detection, and auxiliary air cell addition. In this way, the modeling of the alternating boundary condition can be achieved. The contact forces at each contact pair are computed based on the penalty formulation for each time step. A Coulomb friction model is integrated to simulate stick-slip contact motion. The details of the nonlinear contact LISA formulation can be found in Ref [11].

Parallel Computing Using Compute Unified Device Architecture

In this research, the contact LISA algorithm was implemented using CUDA technology and executed in parallel on GPUs (NVIDIA GeForce Titan X with 3072 CUDA cores). There are two major characteristics of the current contact LISA formulation that enables the computation to be expedited. First, LISA is massively parallel. This is because the computation of a general node or a contact node only depends on the solutions of its eighteen neighboring nodes at the previous two time steps. Thus, the behavior of each node is independent from the others at the target time step, i.e., the computation of each node can be carried out individually in parallel. Second, the wave propagation simulation tasks usually require dense discretization of the structure, resulting in a computationally intensive problem. GPUs, with their massive concurrent thread feature, are suitable to handle such large size problems by distributing the workloads among a large number of functional units and carry out highly efficient parallel computing. The computation of each node is assigned to a functional thread, i.e., each thread gathers the displacements of its eighteen neighboring nodes and one contact pair node (if identified as a contact node) at previous two time steps, process the material properties in the eight surrounding cells, and execute the kernel to compute the displacements of this node at the target time step. Since one of the bottlenecks of a CUDA program is the data transfer between the GPU memory and CPU memory, results are transferred only sporadically (every 10-30 steps depending on the frequency of interest) to minimize such data transfer cost.

RAILWAY FATIGUE DAMAGE DETECTION USING NONLINEAR ULTRASONIC GUIDED WAVES

Figure 1 presents the LISA numerical model for the investigation of guided wave propagation and interaction with a fatigue crack in a rail track. Two lines of surface traction forces are utilized to simulate a pair of transducers generating guided waves into the rail structure. A 100 kHz 10-cycle tone burst is used for wave generation. The ultrasonic waves propagate along the rail track, interact with a fatigue crack, 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, enabling the simulation of wave propagation in an infinite long rail track with a finite dimensional model. A 1-mm mesh size is adopted for the cross-sectional plane, while a 2-mm mesh sized is deployed for the track direction. The time step according to the Courant–Friedrichs–Lewy (CFL) condition is 110.33 ns, which corresponds to a CFL number of 0.99. The 3D LISA grid in Figure 1 shows that the adopted discretization can capture the complex geometric details of the rail track.

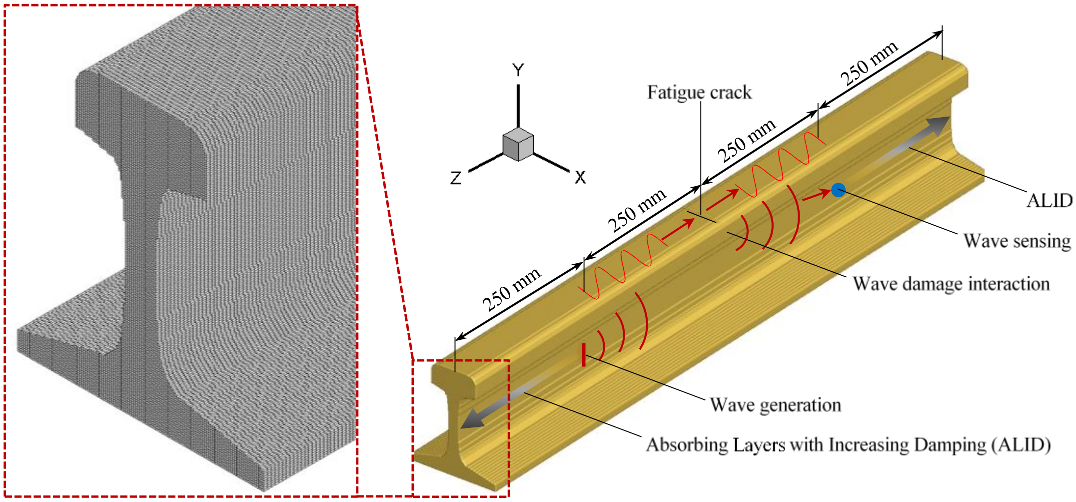


Figure 1: LISA model for guided wave propagation and interaction with a fatigue crack in a rail track.

In order to depict the fatigue damage, a parametric fatigue crack zone is used in the LISA model. Figure 2a shows a typical fatigue zone in a rail track. Figure 2b presents the parametric geometric fatigue zone characterized by the size of *a*. In this study, fatigue crack of progressive sizes are investigated, i.e., a = 0 mm, 5 mm, 10 mm, 15 mm, and 20 mm, corresponding to pristine case, incipient damage case, median damage case, and sever damage case.

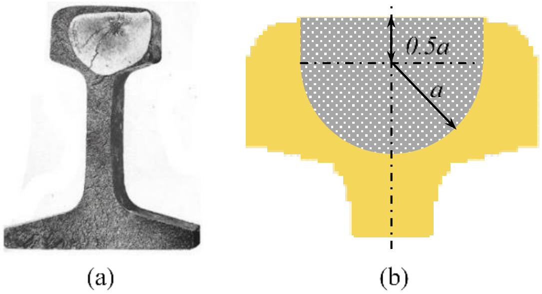


Figure 2: (a) Typical fatigue zone in a rail track [12]; (b) parametric fatigue crack zone in LISA model.

Guided Wave Propagation and Interaction with Damage in a Rail Track

Figure 3 presents the LISA modeling result of guided wave generation, propagation, and interaction with a fatigue crack in a rail track. Figure 3a shows the snapshots of guided wave generation by the line traction forces at 50 μs, guided wave propagation, mode development, and interaction with the crack at 150 μs, as well as guided wave absorption by the ALID boundaries at 300 μs. It can be seen that the guided wave modes are very complex in the rail track. Figure 3b shows the crack open and close phenomenon during the wave damage interaction, which introduces the Contact Acoustic Nonlinearity (CAN) into the sensing signal.

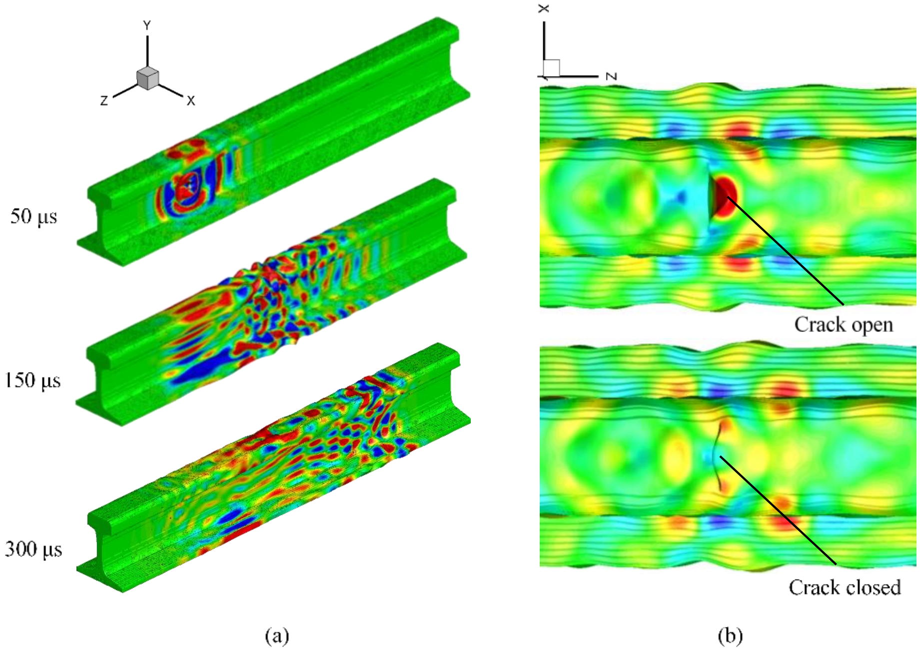


Figure 3: (a) Guided wave generation, propagation, and interaction with a fatigue crack in the rail track; (b) guided wave interacting with crack with crack open and close phenomenon.

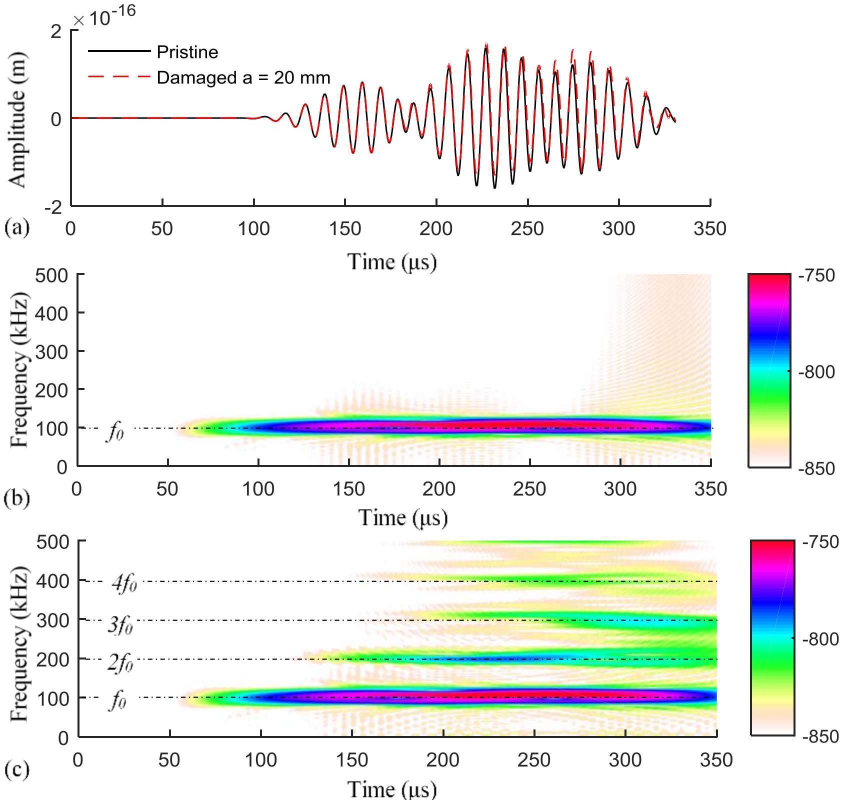


Figure 4: (a) Comparison of time domain sensing signals between pristine and damaged cases; (b) time-frequency domain presentation of the pristine case sensing signal; (c) time-frequency domain presentation of the damaged case sensing signal. Note the appearance of super-harmonic components in the damaged case signal.

Figure 4a presents the comparison of time domain sensing signals between pristine case (a = 0 mm) and the severely damaged case (a = 20 mm). The signals are very complex with multiple wave packets, arisen from the multimodal and dispersive nature of guided waves. According to the conventional linear ultrasonic techniques based on phenomena such as amplitude change, phase shift, or scattering, it is very difficult to make an appropriate assessment of the damage severity. On the other hand, from the perspective of nonlinear ultrasonic features, the damage signature is much more evident. Figure 4b and Figure 4c show the time-frequency domain sensing signals of the pristine case and the severely damaged case, respectively. For the pristine case, only the excitation frequency f_0 exists. However, for the damaged case, in addition to f_0, super-harmonics are present at $2f_0$, $3f_0$, $4f_0$, and so on. Such a unique nonlinear feature allows the early detection of incipient fatigue damage in structures.

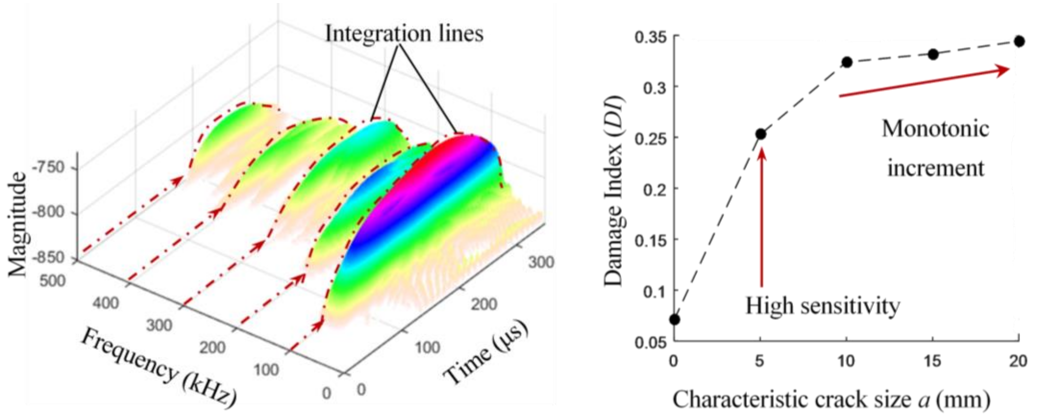
Nonlinear Damage Index for Quantitative Evaluation

In order to quantify the damage severity, a damage index (DI) is developed based on the nonlinear energy proportion in the sensing signal. Figure 5a shows the 3D view of the time-frequency sensing signal of the severely damaged case. The magnitude represents the energy participation of each frequency component along the time history. Admittedly, certain wave modes may possess better sensitivity over others in terms of nonlinear interaction with the crack, but for such a complex problem, an ideal damage index should be able to capture the nonlinear features of each wave mode.

Thus, the time domain integration is used at the fundamental and super-harmonic frequencies to construct the DI, which is given by

$$DI = \sqrt{\frac{\sum_{n=1}^{N}\int_{0}^{t} P\left(t, nf_{0}\right) dt}{\int_{0}^{t} P\left(t, f_{0}\right) dt}} - \sqrt{\frac{\sum_{n=1}^{N}\int_{0}^{t} P\left(t, \left(n+\frac{1}{2}\right) f_{0}\right) dt}{\int_{0}^{t} P\left(t, f_{0}\right) dt}} \tag{1}$$

where, $P\left(t, nf_{0}\right)$ denotes the magnitude at the n$^{\text{th}}$ super-harmonic location at time t. It should be noted that the magnitude should be elevated above zero by subtracting the minimum base value in the spectral graph. The DI represents the nonlinear energy ratio, designating the degree of nonlinearity in the sensing signal. The first term consists of the integration over the “peaks” of the spectrum, while the second term is the integration over the “valleys” of the spectrum serving as the inherent baseline. By subtracting the inherent baseline, this DI becomes a baseline free measurement. Figure 5b presents the damage index results for various crack sizes. It can be noticed that the DI is of high sensitivity; even at incipient damage level (*a* = 5 mm), the DI increased noticeably. The DI also grows monotonically with the damage severity, which allows the monitoring of crack propagation and the quantification of the damage severity.



(a) (b)

Figure 5: (a) 3D view of the time-frequency domain sensing signal for *a* = 20 mm crack case; (b) damage indices for various crack sizes with high sensitivity and monotonic increment.

CONCLUDING REMARKS

This paper presented a numerical study of in-situ damage detection technique based on a nonlinear ultrasonic methodology. A LISA model was constructed to study the guided wave generation, propagation, and interaction with a fatigue crack in a rail track. LISA is capable of modeling the complex nonlinear guided wave phenomena. The distinctive super-harmonic generation feature was observed in the sensing signals from the damaged cases. A damage index was developed based on the nonlinear energy proportion of sensing signals. The numerical case study results for various crack sizes showed that the damage index was of high sensitivity and was capable of monitoring the growth of the fatigue crack. This nonlinear technique is promising for practical applications for the health monitoring railway infrastructures.

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