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GNSS: A Graph Neural Network Surrogate for Guided Wave Propagation in Beams

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The simulation of high-frequency wave propagation in structural components is computationally demanding due to the need for fine spatial and temporal discretizations. Traditional numerical methods such as Finite Element Analysis (FEA) are accurate but prohibitively slow for applications requiring real-time response or extensive parametric studies, such as Structural Health Monitoring (SHM). Graph Neural Networks (GNNs) have emerged as promising surrogate models for physical simulations.

In this work, we present the Graph Network-based Structural Simulator (GNSS), a locality-preserving GNN framework designed as a fast surrogate model for structural dynamics. GNSS leverages the encode-process-decode paradigm and combines three technical innovations tailored to wave-dominated problems: (i) a local-coordinate formulation for node kinematics, which avoids catastrophic cancellation in finite-difference velocities; (ii) a sign-aware acceleration loss, which reduces phase errors in long rollouts; and (iii) a wavelength-informed connectivity radius, which aligns the message-passing neighborhood with physically meaningful interaction scales.

The proposed model is validated on a case study involving guided wave propagation in a beam excited by a 50 kHz Hanning-modulated pulse. We evaluate on a reflection-free interior region of the beam, isolating wave kinematics from boundary effects. Results show that GNSS accurately predicts the transient response over hundreds of timesteps, preserving both the carrier frequency and the wave-packet group velocity, and generalizes to unseen excitation locations along the beam. Compared with an explicit finite element baseline, GNSS achieves substantial inference speedups while maintaining high spatial and temporal fidelity. These findings highlight GNSS as a competitive alternative for the efficient simulation of wave-dominated structural problems.

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