

The work described in this document was performed by Transportation Technology Center, Inc., a wholly owned subsidiary of the Association of American Railroads.

### Key Findings:

- The approach proposed by UIUC shows potential to measure rail longitudinal stress because it shows sensitivity to thermally induced axial stress in rail. It also provides mobility and convenience through a simple testing setup and contactless response reception with a microphone.
- In general, impulse-based vibration offers potential to measure the absolute axial stress without reference with potential mobility in a practical manner. Further development work is needed.
- Results show that crosstie and sub-base conditions have a considerable effect on vibration responses.

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## Use of Impulse-based Vibration for Longitudinal Stress Estimation

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An approach to monitoring stress state fluctuations using impulse-based vibration is proposed by researchers at the University of Illinois at Urbana-Champaign (UIUC). Results of analysis discussed in this *Technology Digest* show several modes of either transverse or vertical vibrations exhibit frequency changes following the measured rail temperature cycle and axial strain gauge readings throughout the day.

Through the technique proposed herein, a light mechanical impulse applied to the rail sets up vibrations that are constituted simultaneously by multiple modes. Finite element simulation initially was applied to study the general behavior of the rail-tie system to the vibrations while the rail is subjected to axial thermal strain. To complement this simulation, experiments were conducted on an outdoor rail section to demonstrate how the condenser microphone can detect high quality (low noise) vibration responses in a contactless fashion. Initial results were favorable. Further development is needed.

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### INTRODUCTION

Reference-free stress determination has been a long-standing research challenge of paramount importance in the fields of experimental mechanics, nondestructive evaluation, and structural health monitoring. Continuous welded rail track cannot freely expand or contract in the axial direction when subjected to temperature variations, which result in compressive or tensile stress. Longitudinal stress monitoring in rails helps mitigate occurrences of track buckling; thus reducing service failures and minimizing the risk of service interruptions.

However, it is difficult to measure rail stress in situ, owing to highly varying boundary conditions and different types of rail, crossties, and fastening systems. Significant research has been conducted to develop nondestructive approaches for rail neutral temperature (RNT) estimation. These efforts include techniques

based on ultrasonic waves,<sup>1</sup> vibration,<sup>2</sup> electromagnetism,<sup>3</sup> and electro-mechanical impedance.<sup>4</sup> Nevertheless, the railroad industry still seeks a practical reference-free solution with potential mobility for in-motion evaluation.<sup>5</sup>

To fulfil those needs, an impulse-based vibrational test is proposed to characterize rail stress by considering multiple vibrational modes under loading and temperature variations.

### IMPULSE-BASED VIBRATION

The theories of vibration of beams and thin rods suggest residual axial load affects the structural modal frequencies and mode shapes, which offers an opportunity to estimate the longitudinal stress state in the rail from vibration measurements.<sup>6</sup>

By applying a mechanical impulse (light impact) event, multiple vibrational modes are simultaneously excited in a structure. The bandwidth of structural response depends on the type and orientation of excitation, which may favor either stretching or flexural modes types. Vibrational modes that are sensitive or insensitive to the axial load may be identified to characterize the axial stress state.

### PRELIMINARY SIMULATION

Preliminary finite element (FE) simulations with Eigenmode analysis were conducted to study the modal frequency variation of the first several track vibrational modes while the rail is subjected to simulated axial thermal strains. All simulations are performed using commercial finite element software.

To study the modal frequency, a simplified, two-dimensional rail-crosstie model composed of a rail cross-section and a crosstie substrate was designed. Figure 1 illustrates examples of the first few mode shapes. The results show that different modes exhibit different patterns of interaction with the substrate, and that the crosstie type (wood, concrete, and steel were considered) significantly influences the rail modal frequency of some modes, but not others. For instance, the first flexural mode in Figure 1a exhibits the least interaction with the substrates compared to the other three modes.

Simulated axial thermal strain (+100 microstrain) was introduced to the two-dimensional model to simulate the state of constrained thermal-induced stress. Both linear and nonlinear constitutive material models were considered. Both material models demonstrate that several modes are more

sensitive to the applied thermal strain. The first flexural mode frequency decreased from 478 Hertz (Hz) to 417 Hz as the compressive strain changed from -100 to 100 micro-strain, while the first stretch mode frequency showed little change across the same strain change

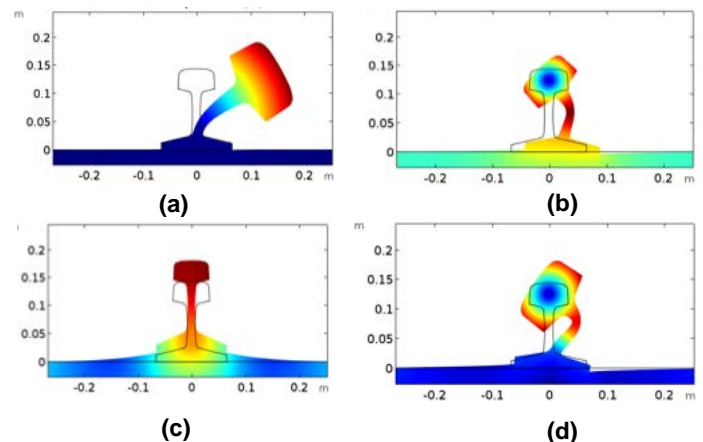


Figure 1. Mode shape examples from FE modal analysis: (a) first flexural mode at 478Hz; (b) second flexural mode at 2649Hz ; (c) first stretch mode at 3245Hz; (d) third flexural mode at 3344Hz. Warmer colors indicate higher total displacement

Generally, these simulation results indicate that substrate materials can significantly affect modal frequencies, particularly in stretch modes, and the sensitivities to thermal stress may vary from mode to mode.

### EXPERIMENT AND ANALYSIS

Experiments were conducted on a 20-meter track panel at the Research and Innovation Laboratory (RAIL) operated by RailTEC at UIUC, see Figure 2. The impulse vibration tests were carried out on a section of rail between crossties 10 and 12, all of which have a consistent crosstie and fastening system setup. Strain gauges in a quarter-bridge configuration were installed in this section on the rail web aligned with the neutral axis. A strain gauge data logger and a thermocouple continuously recorded strain and temperature readings. A condenser microphone was used as the air-coupled (contactless) receiver. The microphone was connected to a signal conditioner, and the data was collected by a data acquisition device.

Vibrational modes were set up by light impacts from a metal mallet at five locations on the rail: at the midspans in the crib between adjacent crossties, and over the crossties, as shown in Figure 2. At each location, transverse or vertical impact orientations were applied on either the side or top of the rail head. The transverse impact especially excites flexural modes

while the vertical impact excites stretch modes. The vibration responses were collected locally near the impact locations using the condenser microphone, amplified and filtered through the signal conditioner, and sampled by the data acquisition device. Each measurement at one location in one impact orientation was repeated at least five times to evaluate consistency in the measurement data.

The entire length of the rail section is outdoors and exposed to sunlight. In order to monitor the change caused by a full heating/cooling cycle throughout the day, experimental data were collected from 9 a.m. through 5 p.m.

The collected vibration signals were analyzed using the discrete Fourier transform to obtain frequency spectra up to at least 50 kHz. The consistency of the measurement repetitions was evaluated by coherence analysis and represented by signal consistency indexes as a function of frequency in the spectrum.<sup>7</sup> These indices serve as an indicator of the frequency range over which the spectral data are consistent. Note that spectral data are later averaged to generate representative spectra for each testing location and orientation.

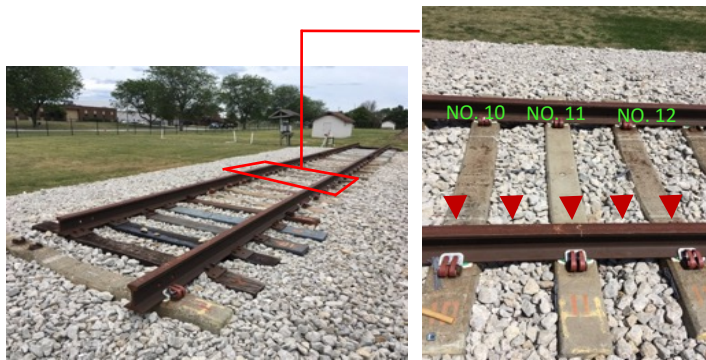


Figure 2. Rail sample used for testing at RAIL, UIUC. The inset (right) shows the specific testing sites and the locations where the vibration was excited and measured on the rail.

**RESULTS AND DISCUSSION**

The time and frequency domain signals from vertical excitation differ from those of transverse excitation, although some vibration modes are common to both configurations. Vibration modes are identified as peak responses in the frequency domain signal. Comparing responses collected at the midspans and over the cross-ties, the data show that vertical responses are significantly affected by the impact location relative to cross-tie and by the cross-tie type, while the transverse responses show relative insensitivity to those conditions. This confirms findings from the FE simulation. To

eliminate excessive complication during measurement, it is more favorable to measure responses in the cribs between adjacent cross-ties.

The variation of temperature-compensated strain readings from the attached gauge follows the rail temperature cycle, indicating developed thermal stress owing to rail expansion and contraction. Mode sensitivity to thermal stress is studied through changes in mode frequencies as a function of temperature. The responses of two different modes subject to the same thermally induced stress are shown in Figures 3 and 4. The two modes show distinct behavior. One mode (transverse response around 1.4 kHz shown in Figure 3) does not change with temperature varying from 23°C to 37°C. However, another mode (transverse response around 36.3 kHz shown in Figure 4) varies and follows the heating and cooling cycle during the day. Other frequency shift phenomena with changing rail temperature also are seen in those sensitive modes, and show promise for the ability to detect instantaneous stress level. Overall, the results collected to date suggest the capability of mode frequency change as a tool to estimate the thermal stress level.

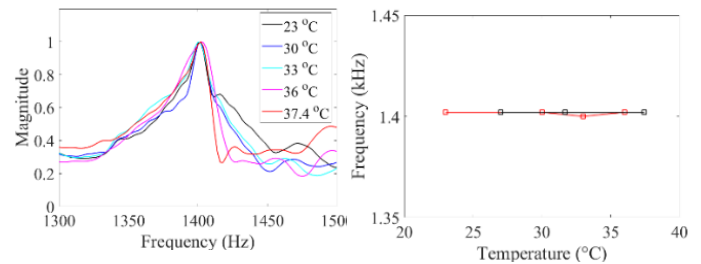


Figure 3. Flexural mode at 1.4 kHz for different rail temperatures (left), and the frequency of the mode vs. rail temperature through the day (right), where the red line indicates the heating process and the black line indicates the cooling process.

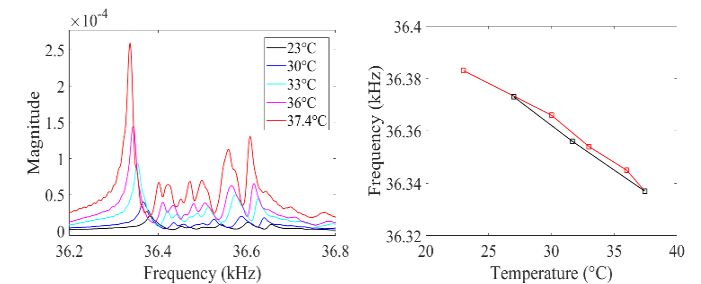


Figure 4. Flexural mode at 36.3 kHz for different rail temperatures (left), and the frequency of the mode vs. rail temperature through the day (right), where the red line indicates the heating process and the black line indicates the cooling process.

## CONCLUSIONS

In this study, an impulse-based vibrational test was proposed to determine thermal stress in CWR track. Preliminary finite element simulations were conducted to study the general behaviors of the track system through the vibration modes while the rail was subjected to axial thermal strain. Different stress and support conditions were considered and observed to affect specific modes differently. An experimental investigation demonstrated the ability to collect high quality (low noise) measurement in contactless fashion. Distinct vibration modes were identified and shown to have distinct sensitivities to thermally induced axial stress and sub-base conditions, confirming the FE simulation results.

In general, impulse-based vibration offers potential to measure the absolute axial stress without reference with potential mobility in a practical manner. Further development work is needed.

## References

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