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ITS Professional Capacity Building Program
T3e Webinar
Smart Sensors and Infrastructures for Transportation

Rail Neutral Temperature Estimation using Impulse Vibration and Machine Learning

Presenter: Yuning Wu (yuning.wu@utah.edu)

Infrastructure Sensing & Experimental Mechanics (iSEM) Laboratory
Department of Civil & Environmental Engineering, University of Utah

In corporation with Dept. of Civil & Environmental Engineering, University of Illinois, Urbana-Champaign

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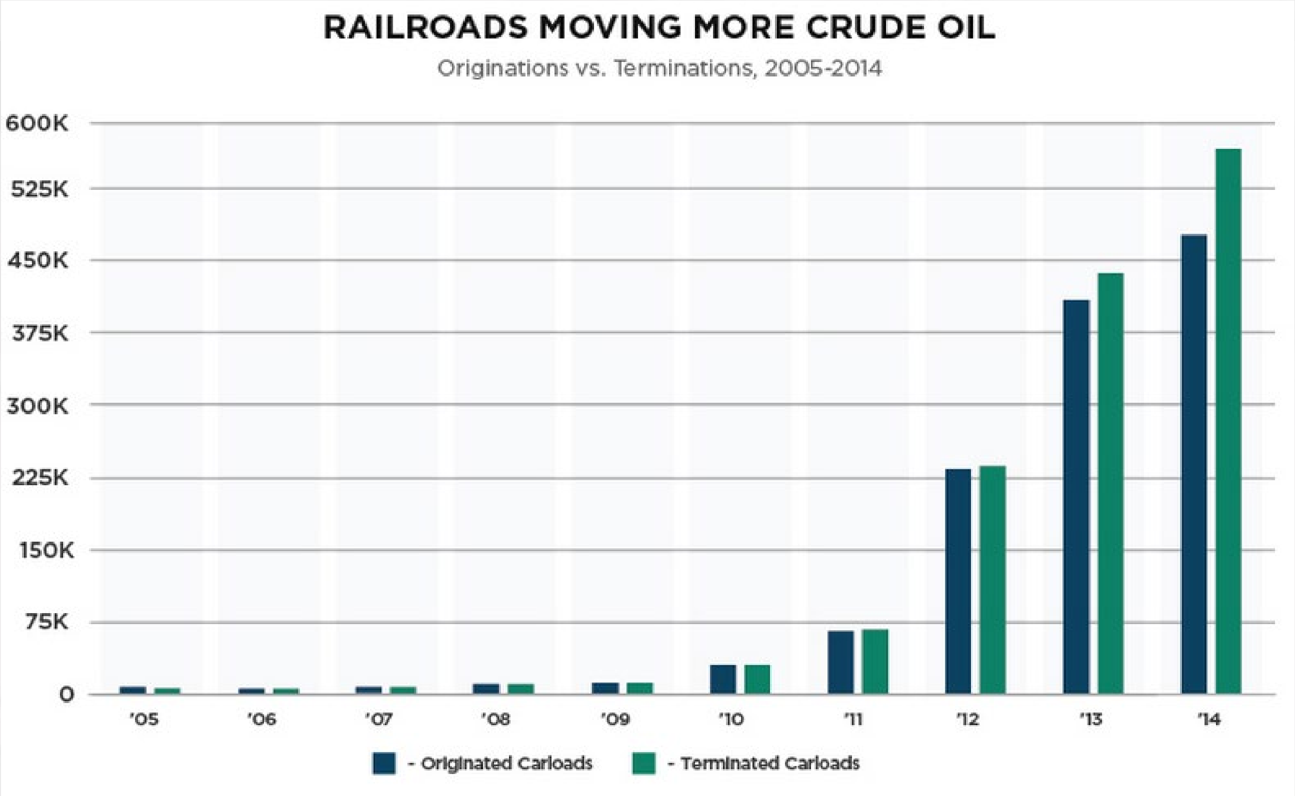
Outline

1. Introduction: Motivation & Literature Review
2. Experimental and Numerical Studies
   - Preliminary Experimental Observations
   - On the Existence of ZGV modes in Rails
   - Sensitivity to temperature and axial load
3. ML-RNT Predictive Tool Development
   - Framework Development
   - Field Data Collection
   - System Performance Evaluation
4. Conclusion

Motivation

Simple facts

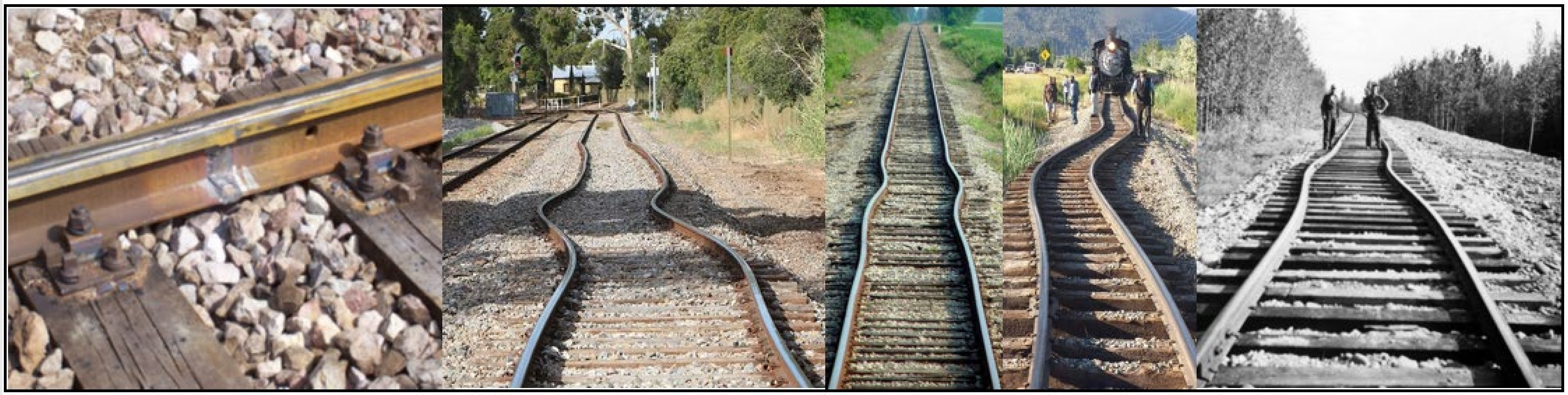
- U.S. ranks 1st by length of railroad networks (**160,141 miles** by 2017)
- The continuous welded rail (CWR) has been widely adopted (**106,500 miles**)
- The U.S. rail networks transported over **1,621.8 million tons** of commodity in 2017
- There are potential increasing demands from railroad industry for safety & efficiency



Source: Bloomberg BusinessWeek

Motivation

Due to lack of expansion joints, CWR develops internal tensile/compressive stresses when the rail temperature is below or above the stress-free temperature.



Source: Gettyimages

2002 Crescent City Amtrak derailment
4 deaths, 142 injuries, $8.3M

2012 Northbrook UP derailment
2 deaths, 31 cars derailed, bridge collapsed, $5.3M

Motivation

Federal Railroad Administration (FRA) safety statistics report the 'track alignment irregularities (buckled/sun kink)' as one of the leading causes of train accident.

Sepcific Causes:	Total		Type of Accident		Reportable Damage			Casualty	
	Cnt	%	Coll	Der	Other	Amount	%	kld	Nonf
T207- Detail fracture - shelling/head check	267	7.4	2	265	-	89,306,643	13.4	2	5
T109- Track alignment irreg(buckled/sunkink)	152	4.2	1	150	1	85,063,378	12.8	2	3
T220- Transverse/compound fissure	208	5.8	-	206	2	44,927,561	6.7	0	0
T110- Wide gage(defective/missing crossties)	555	15.5	1	552	2	42,904,761	6.4	0	7
T001- Roadbed settled or soft	109	3	2	105	2	34,211,301	5.1	0	16
T213- Joint bar broken (compromise)	9	0.3	-	9	-	25,851,789	3.9	0	132
T221- Vertical split head	148	4.1	1	147	-	24,930,317	3.7	0	3
T202- Broken base of rail	120	3.3	-	120	-	24,579,199	3.7	0	3
T299- Other rail and joint bar defects	46	1.3	-	45	1	24,044,945	3.6	0	3
T102- Cross level track irreg.(not at joints)	86	2.4	-	84	2	22,277,255	3.3	0	0
T201- Bolt hole crack or break	51	1.4	1	50	-	20,177,698	3	0	1
T002- Washout/rain/slide/etc. dmg -track	31	0.9	-	28	3	18,648,983	2.8	1	11
T111- Wide gage(spikes/other rail fasteners)	163	4.5	-	163	-	16,795,744	2.5	0	1
T210- Head and web sep(outside jt bar limit)	133	3.7	-	132	1	16,727,662	2.5	1	3

- Over 200M reportable damage and nearly 100% derailment rate over the past two decades.
- Thermal buckling prevention is high priority industry goal.

Source: https://safetydata.fra.dot.gov/OfficeofSafety

Research Problem

Industrial demand - to facilitate the thermal stress management within CWR structure, the knowledge of the stress-free temperature or **Rail Neutral Temperature (RNT)** is critical.

	Item #	*Phenomena/ Technique*	*Work / Investigator / Exp. Publication*
Static deformation	1	Rail uplift (VERSE)	Samavedam and Kish 1987 & 1995
	2	Strain measurement (Wheatstone bridge)	Harrison et al. 1999, Liu et al. 2018
	3	Strain measurement (DIC)	Knopf & Rizos et al. 2020
	4	Strain measurement (Hole-drilling)	Zhu & Lanza di Scalea 2017, Harrington et al. 2017
Vibration	5	D'stressen	Read & Shust 2007
	6	Vibration (Modal frequency, mode shape)	Boggs & Murray 1994, Koob 2005, Damljanović & Weaver 2006
	7	Vibration (Video imaging)	Sefa Orak & Rizzo et al. 2018
Ultrasound	8	Acoustoelastic effect (Rayleigh wave, flexural modes, birefringence, horizontal shear waves)	Egle & Bray 1979, Man & Paroni 1996, Gokhale & Hurlebaus 2008, Hurley 2014, Albakri & Tarazaga 2018
	9	Diffuse ultrasound	Turner et al. 2011
	10	Nonlinear ultrasonic guided waves	Bartoli et al. 2010, Nucera & Lanza di Scalea 2014a & 2014b
Local stiffness	11	Electromechanical impedance method	Phillips et al, 2012, Zhu & Lanza di Scalea, 2016
	12	Nonlinear solitary waves	Nasrollahi & Rizzo 2018 & 2019
	13	Magnetic (MAPS-SFT, metal magnetic memory, magnetic Barkhausen noise)	Read 2010, Wegner 2007, Zhang et al. 2011 Shu et al. 2016
	14	Piezospectroscopy	Kim & Yun 2018 & 2019

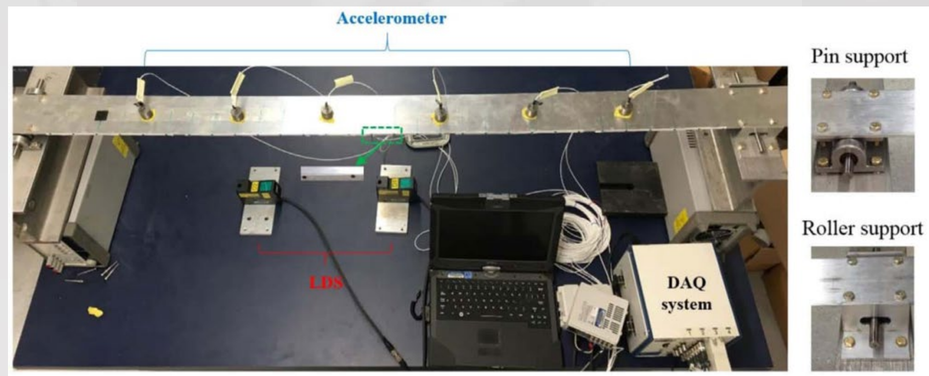
Research Problem – to determine RNT or longitudinal thermal load in a *nondestructive* and *nondisruptive* manner without the need of reference measurement at zero stress state with a *reasonable accuracy* ($\pm 10°F$).

Source: https://safetydata.fra.dot.gov/OfficeofSafety

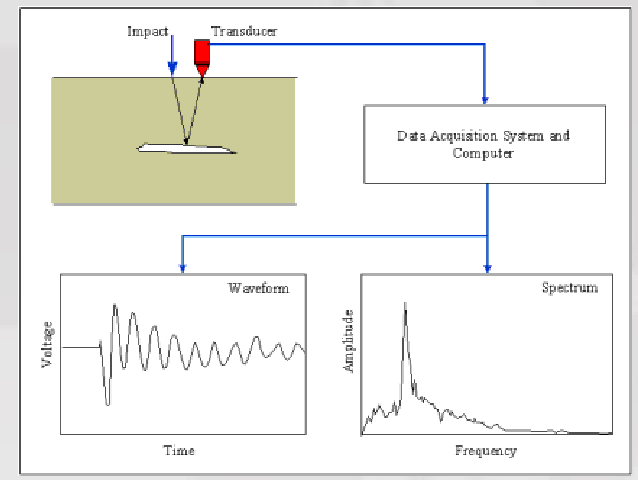
Experimental & Numerical Studies

- Impulse vibration test has been widely used in experimental modal analysis, structural dynamics testing, impact echo test, and so on.

Source: Siemens*

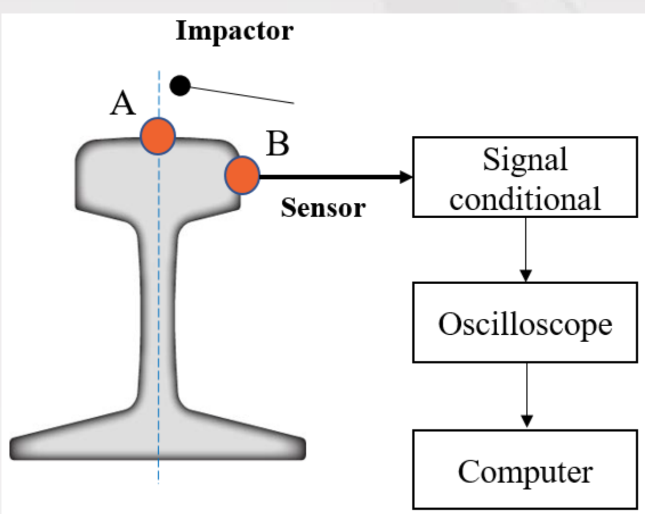


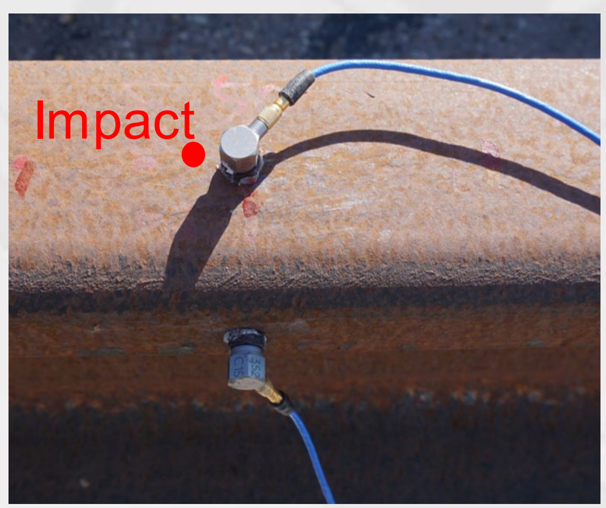
Source: Feng**



Source: ***

- Why not try the impulse vibration test on rails?





Impact and detection within/close to **the same cross section**

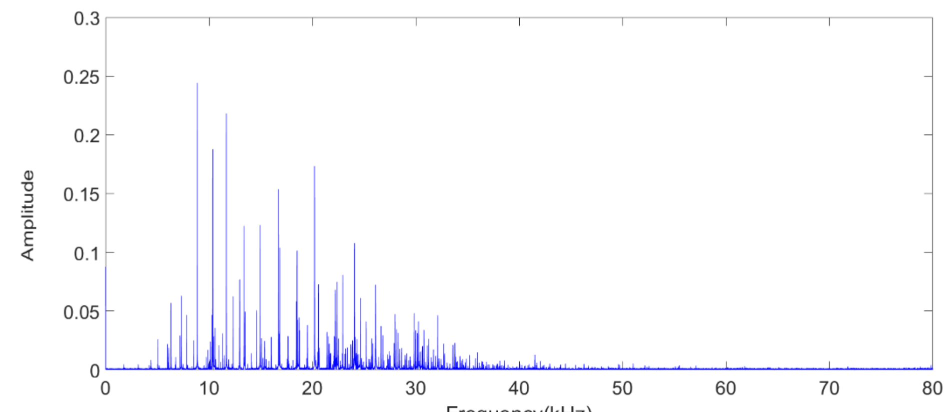
- Sample 0 - 3 ft rail sample
- Sample 1 - 60 ft rail sample
- Sample 2 – CWR

*Siemens Webinar "Understand the basics and mathematics behind modal analysis"
**D. Feng et al "Experimental validation of cost-effective vision-based structural health monitoring," MSSP 2017.
*** NDT.net

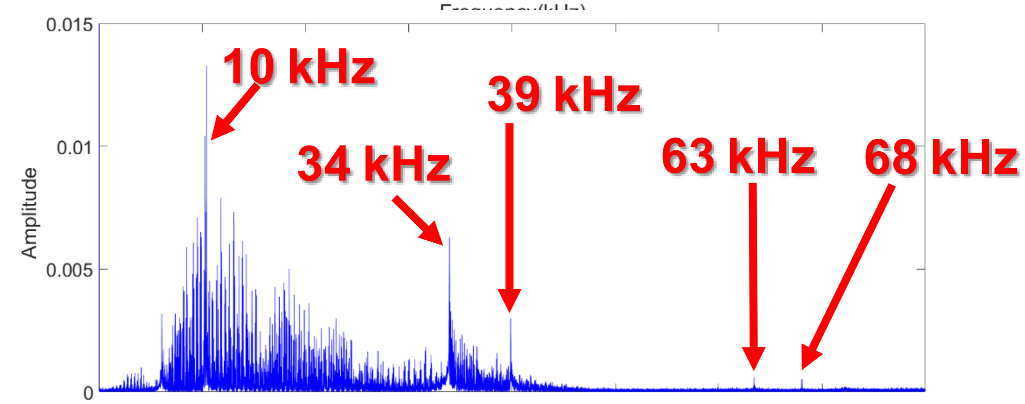
Experimental & Numerical Studies

- Vibration spectrum from rail samples

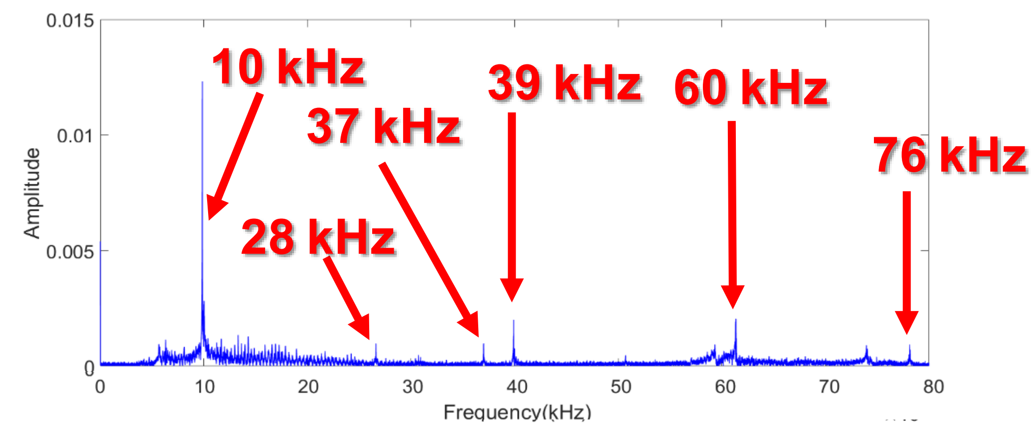
Sample 0
- 3 ft rail sample



Sample 1
- 60 ft rail sample



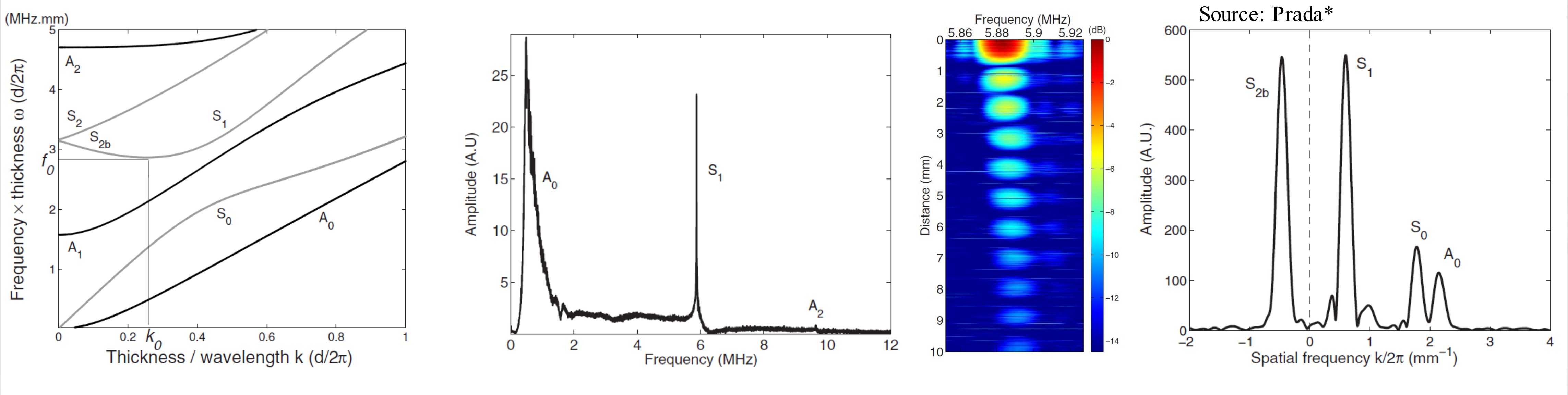
Sample 2
- CWR with full track setup



Experimental & Numerical Studies

Existence of ZGV Modes in Rails

Are we generating the Zero-group Velocity modes in the rails? Note $V_g = \partial\omega/\partial k$



- Hypothesis 1: There exists Zero-group Velocity (ZGV) mode(s) in free rails, and the specific mode(s) can be generated and detected by impulse vibration test.
- Hypothesis 2: The Zero-group Velocity (ZGV) frequencies in rails will be affected by both temperature and axial load.

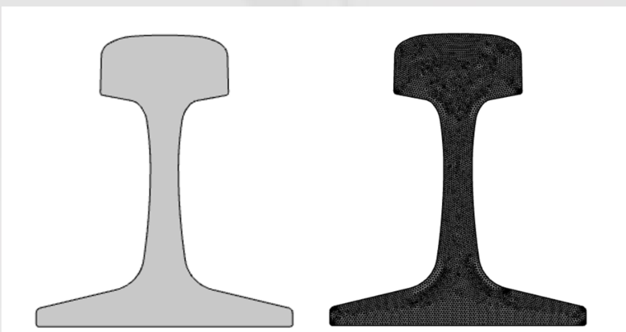
*Prada et al "Local vibration of an elastic plate and zero-group velocity Lamb modes" JASA 2008

Experimental & Numerical Studies

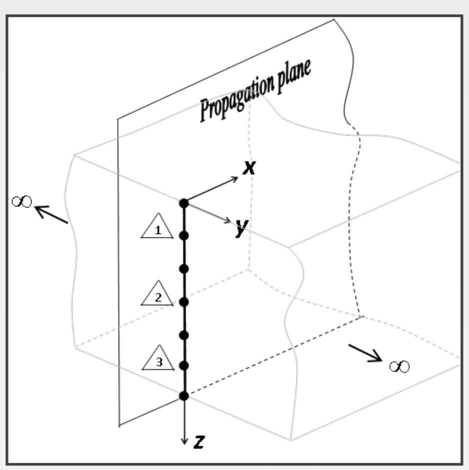
Existence of ZGV Modes in Rails

- **S**emi-**A**nalytical **F**inite **E**lement (**SAFE**) analysis to calculate dispersion curves of rails

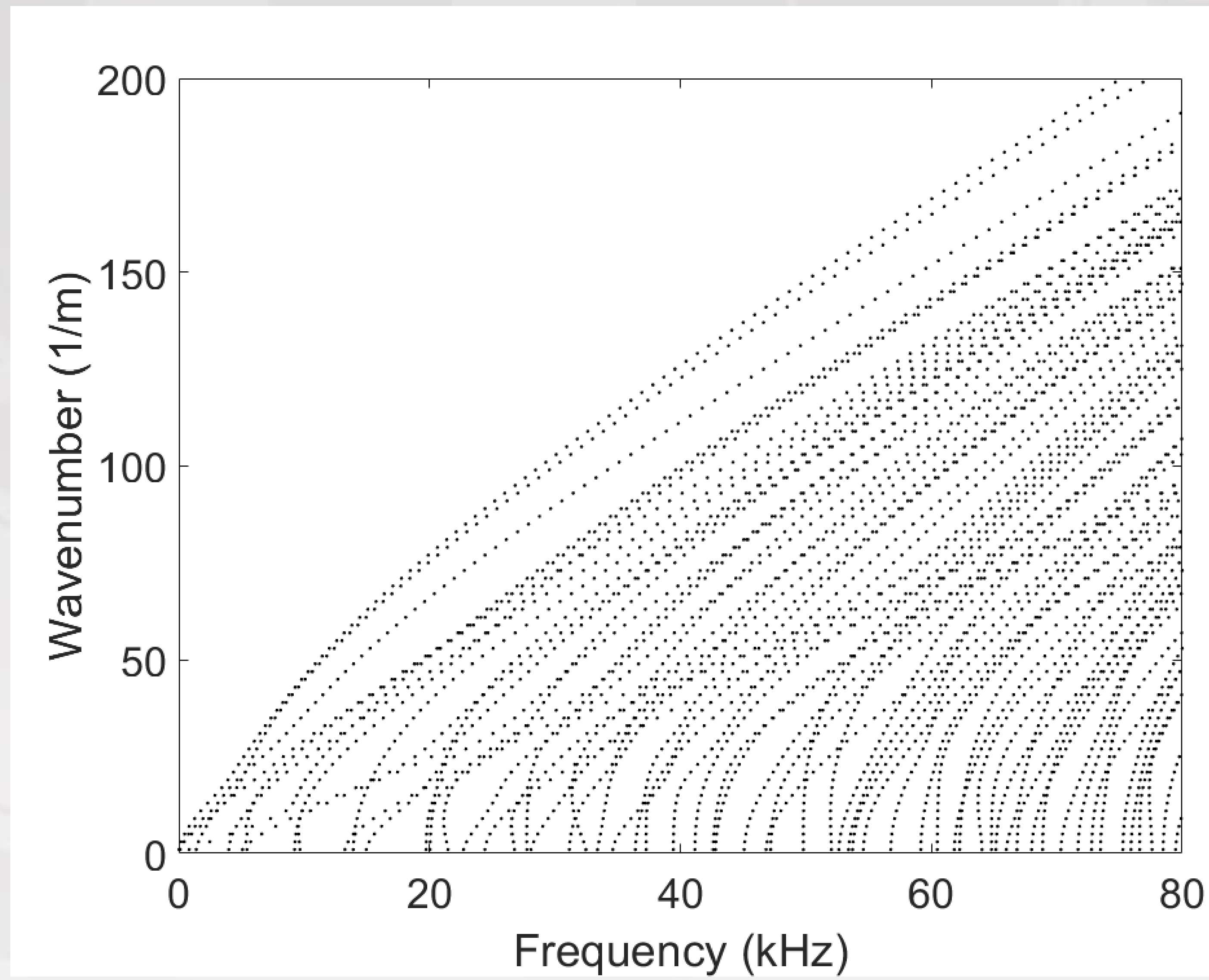
  - Waveguide's cross section is discretized by finite elements



  - The displacements along the wave propagation is assumed as an analytical harmonic exponential function, $e^{-i\omega t}$.



$$\mathbf{u}^e(x,y,z,t) = \begin{bmatrix} \sum_{n=1}^{3} N_n(y,z)U_{xn} \\ \sum_{n=1}^{3} N_n(y,z)U_{yn} \\ \sum_{n=1}^{3} N_n(y,z)U_{zn} \end{bmatrix}^e e^{i(kx-\omega t)}$$



Experimental & Numerical Studies

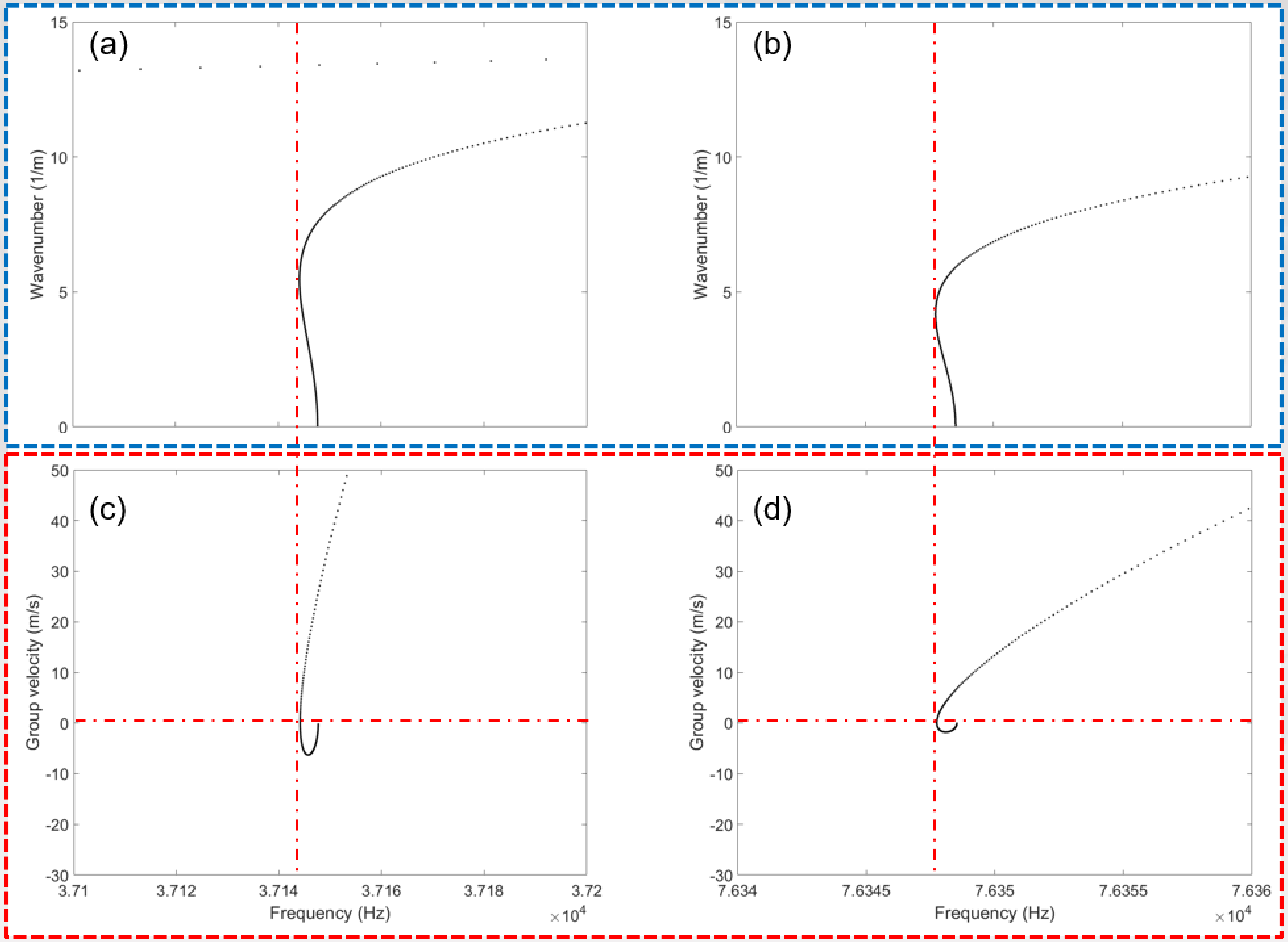
Existence of ZGV Modes in Rails

- Semi-Analytical Finite Element (SAFE) analysis to calculate dispersion curves of rails

Zoom-in k-f figure

Note $V_g = \partial\omega/\partial k$

Group velocity



provides a strong evidence that ZGV modes exist in free rails. (Hypothesis 1)

Experimental & Numerical Studies

Eigenmode analysis - predict the behavior of Zero-group Velocity (ZGV) frequencies

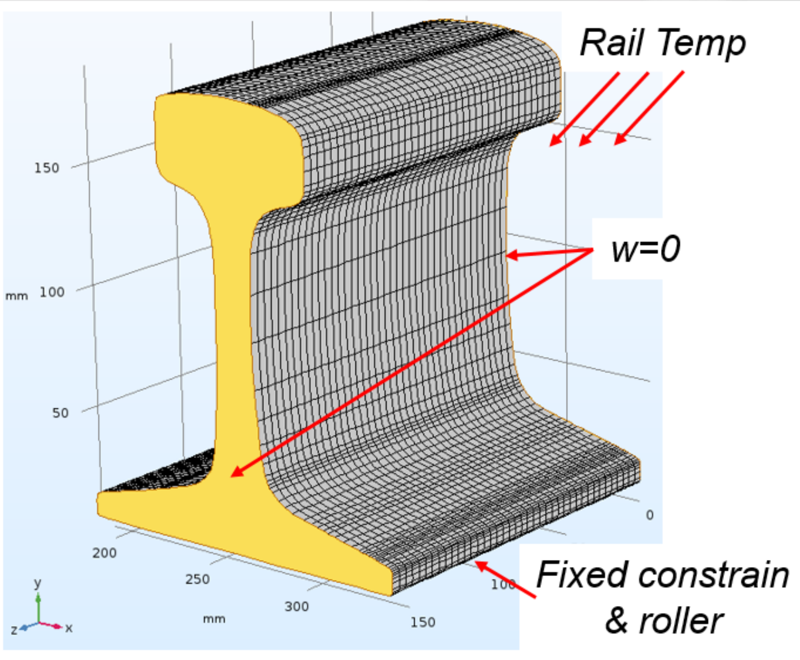
- Hypothesis 2: The Zero-group Velocity (ZGV) frequencies in rails will be affected by both temperature and axial load.
  - ➢ Simulations of rails when subjected temperature variation and axial load
  - ➢ Perform data collection when rail is subjected to temperature variations
- Two-step model creation

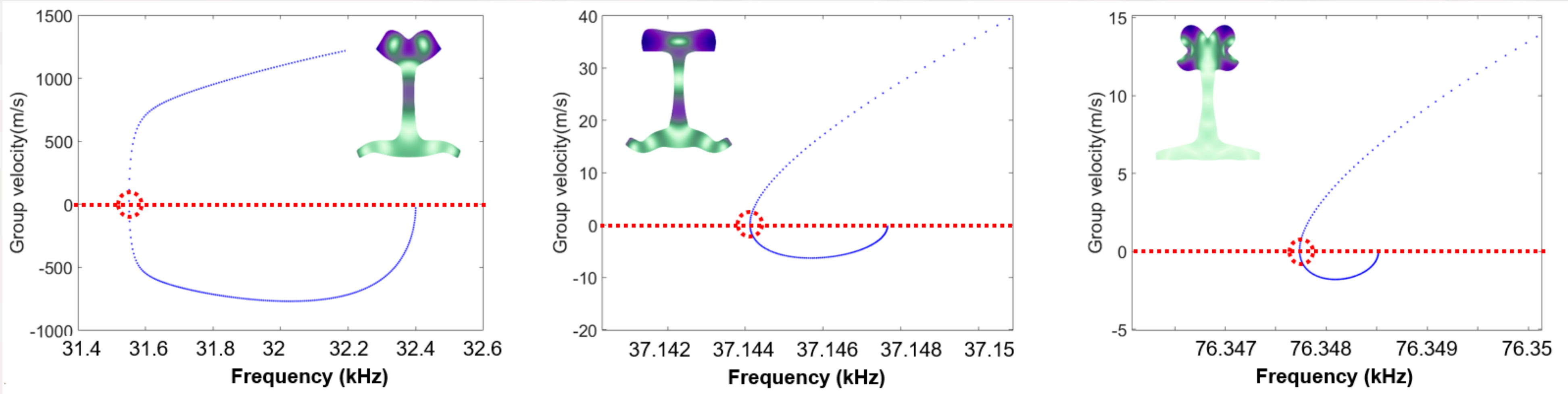
Two-step Analysis
Step 1: Stationary (updated stiffness matrix)

Step 2: Eigenfrequency (eigenmodes & frequencies)

Boundary Conditions
Step 1: Prescribed displacement (w=0), fixed constrain & roller

Step 2: Prescribed displacement (w=0)



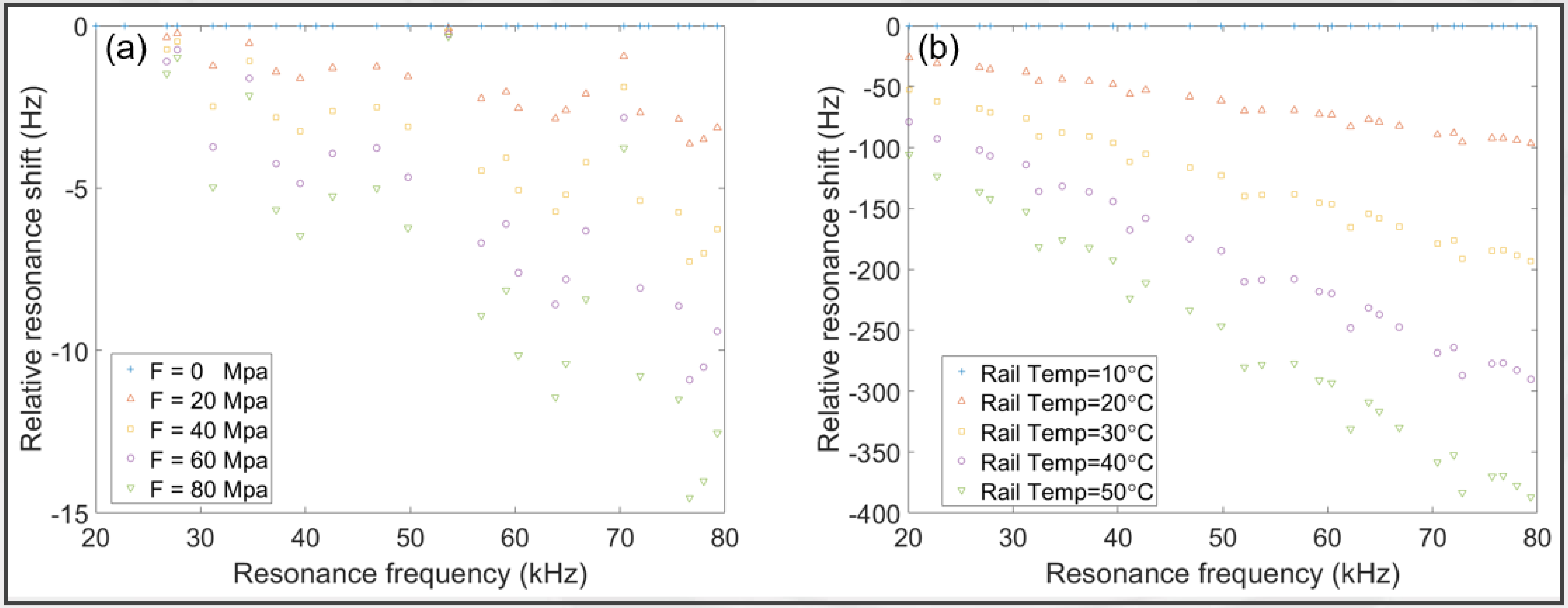


Experimental & Numerical Studies

Eigenmode analysis - predict the behavior of Zero-group Velocity (ZGV) frequencies

Behaviors of confined CWRs subjected to temperature and longitudinal load were analyzed using eigenmode analysis

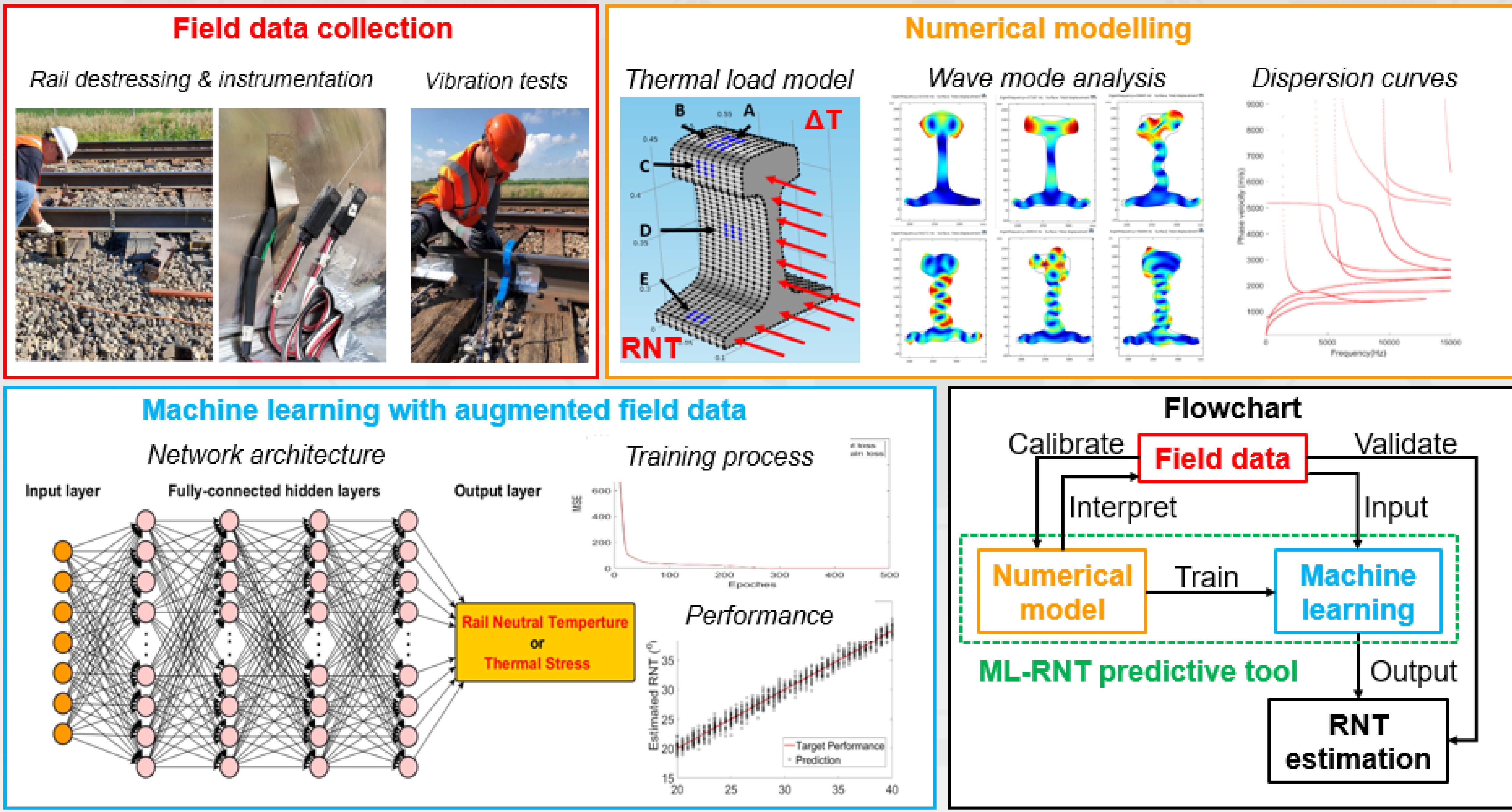
Resonance frequency shifts due to (a) longitudinal force (b) rail temperature



- Modest extent of variation in local vibration modal frequencies introduced by longitudinal load
- Largest extent of variation in local vibration modal frequencies introduced by the rising temperature (Hypothesis 2)

ML-RNT Predictive Tool

Framework Development

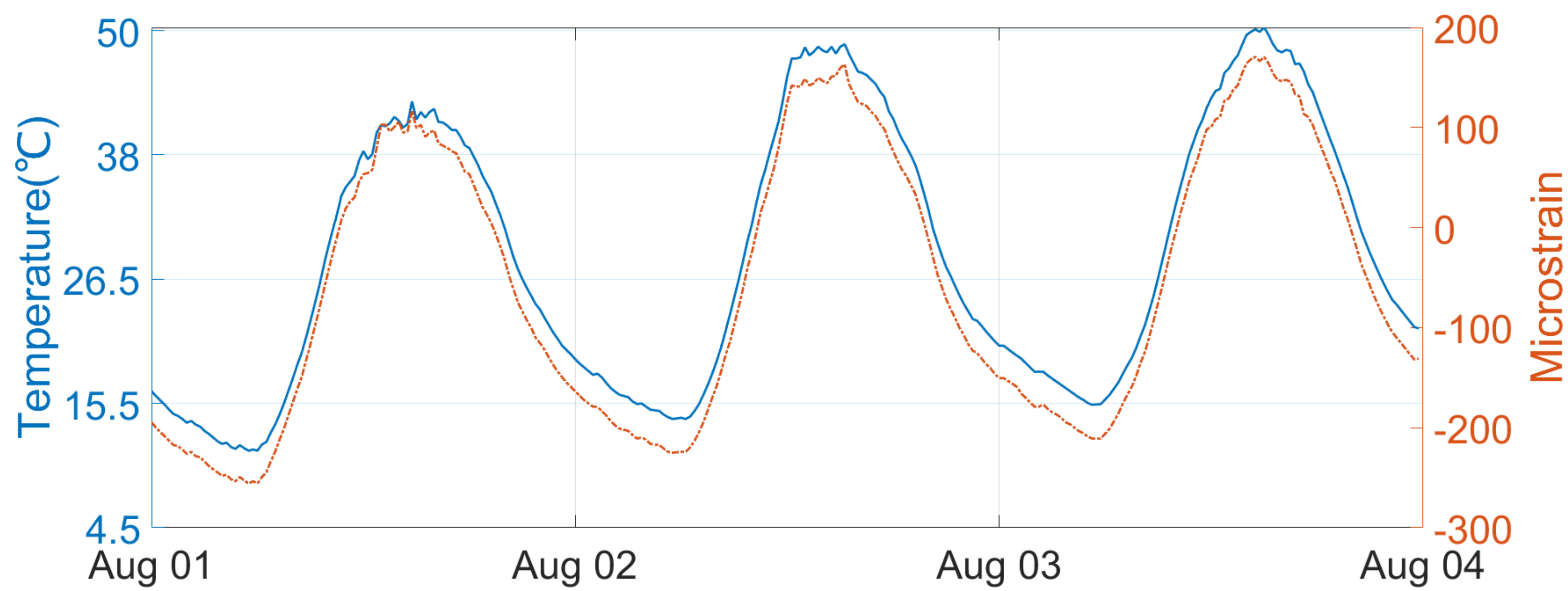


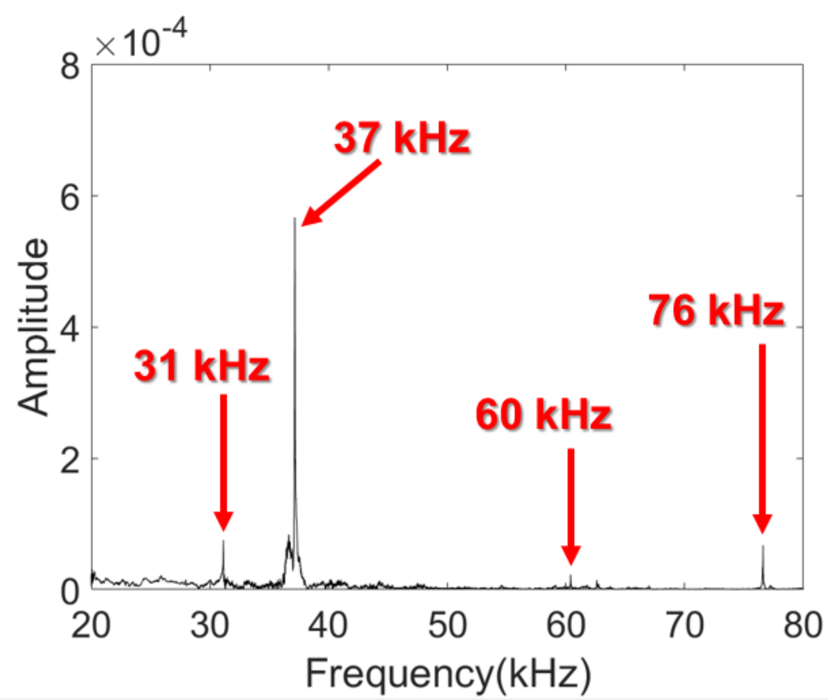
ML-RNT Predictive Tool

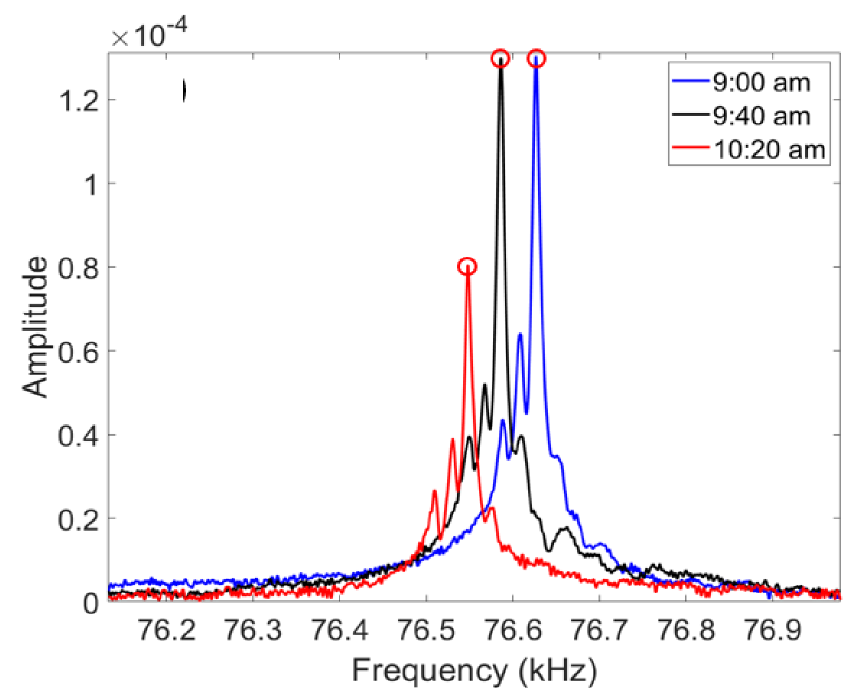
Data Collection & Analysis – Revenue-service site

ML-RNT Predictive Tool

Data Collection & Analysis – Revenue-service site







ML-RNT Predictive Tool

Regression Model for RNT estimation

A regression model was proposed:

- Input: rail vibration modal parameters
- Output: Rail neutral temperature(RNT)

A mathematical formulation to relate CWR modal features f_{k}^{T} to RNT is given by

$$\begin{Bmatrix} f_1^T \\ f_2^T \\ \vdots \\ f_{n-1}^T \\ f_n^T \end{Bmatrix} = \begin{Bmatrix} f_1^{RNT} \\ f_2^{RNT} \\ \vdots \\ f_{n-1}^{RNT} \\ f_n^{RNT} \end{Bmatrix} + \begin{bmatrix} S_1^{\sigma} & S_1^{T} \\ S_2^{\sigma} & S_2^{T} \\ \vdots & \vdots \\ S_{n-1}^{\sigma} & S_{n-1}^{T} \\ S_n^{\sigma} & S_n^{T} \end{bmatrix} \begin{Bmatrix} -E\alpha(T-RNT) \\ T-RNT \end{Bmatrix}$$

thermal stress: $-E\alpha(T-RNT)$

measured multiple modal features on rail temperature

measured multiple modal features on RNT

thermal load sensitivity

temperature sensitivity

This all represents a simple regression model in the form of $y = mx + b$, where independent (RNT and T) and dependent (f_{k}^{T}) variables are related to each other through unknown coefficients ($\boldsymbol{S}_k^T$, $\boldsymbol{S}_k^{\sigma}$, and f_k^{RNT}) that need to be determined through a regression analysis

ML-RNT predictive system

ML-RNT prediction results

Use the resonance frequency of the ZGV mode at 76 kHz and rail temperature as input to the NN

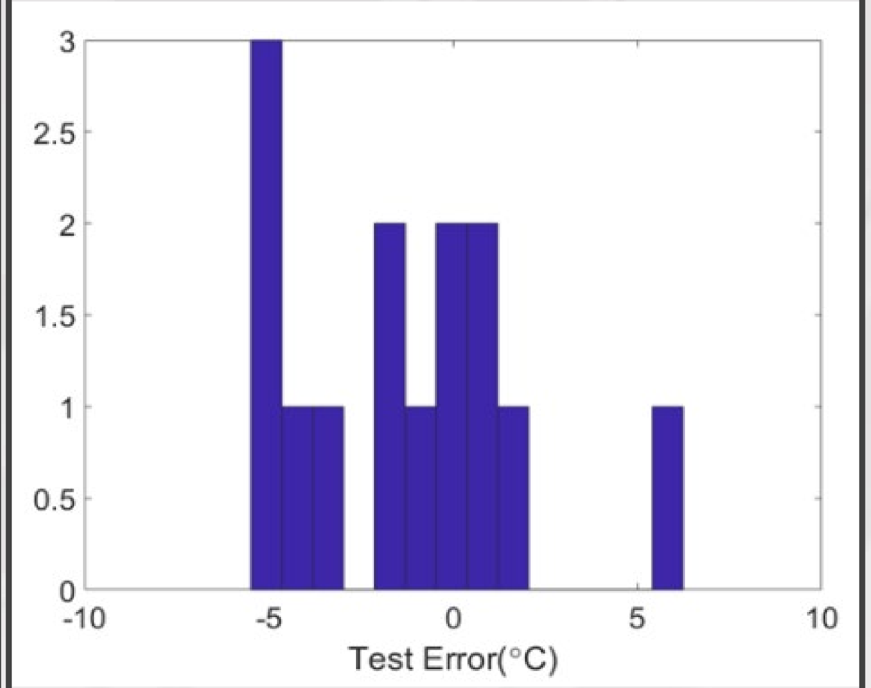
Model performance

Measured frequency (Hz)	Model frequency (Hz)	Model error (Hz)
76628.6	76628.4	0.2
76588.6	76580.3	8.3
76548.6	76547.9	0.7
76691.8	76690.4	1.4
76657.8	76658.4	-0.6
76600.3	76604.0	-3.7
76654.6	76654.7	-0.1
76614.6	76614.7	-0.1
76582.6	76577.0	5.5
76571.8	76571.0	0.8

ML-RNT prediction using 76kHz

Measured RNT (°C)	Estimated RNT (°C)	Estimation error (°C)
32.59	31.99	-0.6
32.49	21.37	-11.12
33.03	32.67	-0.36
32.70	29.97	-2.73
32.50	31.60	-0.90
32.92	36.45	3.53
31.89	33.68	1.79
31.72	32.89	1.16
31.67	24.99	-6.67
31.5	31.18	-0.32

Prediction error



The error of RNT estimation is well bounded within ± 5 °C range on vibrational data collected at the revenue-service site.

Summary

- The contactless sensing technique can effectively promote the local vibration modes in CWRs, which are distinctive from the ones obtained in lab.
- The proposed sensing technique was deployed for field data collection over a wide range of temperature and thermal stress levels.
- Numerical models were developed to understand and predict the CWR vibrational behavior under the influence of temperature and RNT.
- An excellent agreement (discrepancies less than 0.01%) between model and experimental results were obtained.
- The performance of the developed RNT predictive tool was evaluated using field measurements as input. And the proposed framework can support an estimation accuracy of ± 5 ^{o}C, when measurement or model noise is low.

Acknowledgement

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Thanks!

Any questions?

Yuning Wu (yuning.wu@utah.edu)

Infrastructure Sensing & Experimental Mechanics (iSEM) Laboratory

Department of Civil & Environmental Engineering, University of Utah