A WAYSIDE SYSTEM BASED ON ULTRASONIC GUIDED WAVES FOR
MEASUREMENT OF NT IN CWR

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ABSTRACT

The University of California at San Diego (UCSD), under a Federal Railroad Administration (FRA) Office of Research and Development (R&D) grant, is conducting research to develop a system for in-situ measurement of the rail Neutral Temperature in Continuous-Welded Rail (CWR). It is known that CWR can break in cold weather and can buckle in hot weather. Currently, there is a need for the railroads to know the current state of thermal stress in the rail, or the rail Neutral Temperature (rail temperature with zero thermal stress), to properly schedule slow-order mandates and prevent derailments.

UCSD has developed a prototype for wayside rail Neutral Temperature measurement that is based on non-linear ultrasonic guided waves. Numerical models were first developed to identify proper guided wave modes and frequencies for maximum sensitivity to the thermal stresses in the rail web, with little influence of the rail head and rail foot. Experiments conducted at the Large-scale Rail NT Test-bed indicated a rail Neutral Temperature measurement accuracy of a few degrees. Field tests are planned at the Transportation Technology Center (TTC) in Pueblo, CO in June 2012 in collaboration with the Burlington Northern Santa Fe (BNSF) Railway.
INTRODUCTION

Most modern railways use Continuous Welded Rail (CWR). Inherent in these structures are safety risks due to the absence of expansion joints to accommodate thermally induced expansion and shrinkage. These effects can cause rail buckling in hot weather and rail breakage in cold weather (Fig. 1). According to FRA Safety Statistics data (1), in 2010 irregular track alignment from buckling or sunkink was the first cause of train accidents in the U.S. within the categories of track, roadbed and structures, responsible for the highest cost of $17M or 15% of the total damage cost from these categories.

![Figure 1- Buckling in a Continuous Welded Rail from thermal stresses.](image)

Railroads manage the thermal stress problem of CWR by installing the rail at a specific level of prestress. This ensures that the rail will stay at relatively safe thermal stress levels throughout the ambient temperature fluctuations.

A related critical parameter in CWR is the rail *Neutral Temperature*. It is defined as the rail temperature at which the net thermal force in the rail is zero. Unfortunately, the rail Neutral Temperature changes in service due to several parameters, including rail kinematics (creep,
breathing, ballast settlement, etc..) and rail maintenance (installation, realignment, distressing, broken rail repairs, etc..). Consequently, even for a known rail “laying” or “anchoring” temperature, the Neutral Temperature for a rail in service is generally unknown.

The well-known formula that governs the thermal loads in CWR is:

\[ P = \alpha E A (T - NT) \]  

where \( P \) is the applied thermal load, \( \alpha \) is the coefficient of thermal expansion of steel, \( E \) is the Young’s Modulus of steel, \( A \) is the rail cross-sectional area, \( T \) is the rail temperature, and \( NT \) is the rail Neutral Temperature.

The measurement of the rail Neutral Temperature in-situ remains a long-standing problem for the railroads and one that has been the subject of several investigations (2-6). The railroads can benefit from a system able to measure the rail Neutral Temperature in-situ with a sufficient level of accuracy (+/- 5 °F) and without the effects of rail supports (no tie-to-tie variations) or the effects of residual stresses and changes in geometry (wear) of the railhead.

**NONLINEAR GUIDED WAVES FOR RAIL NEUTRAL TEMPERATURE MEASUREMENT**

UCSD is exploring a new approach for the measurement of the rail Neutral Temperature that is based on nonlinear ultrasonic guided waves (7, 8). The expected advantages of this approach include:

- NT measurement accuracy to within ± 5 °F.
• No need for reference value of stress.
• No sensitivity to rail supports (tie-to-tie variations) or to residual stresses/changes in geometry of the railhead.
• Potentially, no need for calibration for different rail sizes/manufacturers.

In order to develop the system, sophisticated numerical models of nonlinear guided waves propagating in a rail were developed (9-12). The nonlinear models were developed based on the higher-order terms arising in a constrained structure subjected to thermal variations. The physical basis for the development of nonlinear effects in a constrained waveguide subjected to thermal variations is the inter-atomic potential which is schematized in Fig. 2. This figure shows that when a structure is heated and prevented from expanding, a strain energy term, that is at least cubic as a function of strain, arises. The cubic strain energy term gives rise to nonlinearities in the propagating waves.

![Nonlinearity from thermal stresses in a constrained solid subjected to temperature excursions in terms of inter-atomic potential.](image)

**Figure 2-** Nonlinearity from thermal stresses in a constrained solid subjected to temperature excursions in terms of inter-atomic potential.
Coupling the nonlinear formulations with models of guided wave propagation in a rail, guided modes were selected with predominant motion of the rail web. Some of these modes are shown in Fig. 3. The use of these modes for a wayside system avoids any effects of the rail foot (rail supports) and any effects of the railhead (residual stresses and/or changes in geometry such as wear).

![Figure 3](image)

**Figure 3** - Selected nonlinear guided waves propagating predominantly in the rail web with no effect of rail foot or railhead.

**EXPERIMENTAL PROTOTYPE AND LARGE-SCALE EXPERIMENTAL TEST-BED AT POWELL STRUCTURAL LABORATORIES**

A Large-Scale Experimental Test-bed was constructed at UCSD’s Powell Structural Laboratories (Fig. 4). BNSF participated to the construction of this test-bed. The setup is a unique, 70-foot long track of 136lb RE rail. It allows to impose controlled temperature variations through a specially designed rail switch heating wire. The track can be prestressed at varying rail
installation stresses to achieve any value of rail Neutral Temperature. Currently, the track is installed at a 90 °F Neutral Temperature value. The track is heavily instrumented with 48 strain gages, 6 thermocouples, and a number of potentiometers to fully follow its behavior during the heating and cooling cycles.

Figure 4- The Large-Scale Rail NT Measurement Test-bed at UCSD’s Powell Structural Laboratories.

A prototype was designed and constructed for the rail Neutral Temperature measurement (Fig. 5). The system attaches magnetically to the rail web. It contains an ultrasonic transmitter and an ultrasonic receiver. The prototype measures the nonlinearity in the selected guided wave modes propagating within the rail web. The nonlinearity is then related to the level of thermal stress in the rail. The minimum level of nonlinearity exactly corresponds to the state of zero stress, or rail Neutral Temperature.
Figure 5- The prototype developed for rail Neutral Temperature measurement. It is a wayside installation on the rail web.

EXPERIMENTAL RESULTS

Several measurements of the nonlinear guided waves were taken at several locations of the Large-Scale Experimental Test-bed during several heating cycles that brought the track through Neutral Temperature. A typical result is shown in Fig. 6. This figure plots the experimentally measured nonlinear parameter of the selected guided modes as a function of longitudinal thermal strains measured in the track by the temperature-compensated strain gages. The temperature trend is also indicated in this figure. This result shows the expected minimum of the nonlinearity value measured at the state of zero strains (or the rail Neutral Temperature). The accuracy of this result is to within ± 2 °F considering a thermal expansion coefficient for steel of 6.7 microstrain/°F. This is of course an excellent result, if confirmed in the field.
Figure 6- Experimental result showing the nonlinear parameter of the ultrasonic guided wave identifying the rail Neutral Temperature with high degree of accuracy.

NEXT STEPS

A first field test is being planned for June 2012 in coordination with the FRA, Volpe and BNSF at the TTC in Pueblo, CO. The purpose of this field test will be to verify the results obtained in the Large-scale Laboratory Test-bed. Iterations of the system, and additional field tests, will follow.

ACKNOWLEDGMENTS

This work was supported by the U.S. Federal Railroad Administration under University grant# FR-RRD-0009-10-01-00, with Mahmood Fateh from the FRA Office of Research and Development as the Program Manager. Former UCSD Ph.D. students Ivan Bartoli, now at
Drexel University, Stefano Coccia and Ankit Srivastava are acknowledged for their early contribution to this project. Mahmood Fateh, Gary Carr and Leith Al-Nazer of the FRA provided essential technical support and advice throughout this project. John Choros of Volpe Center also gave advice for the construction of the Large-Scale Test-bed at the Powell Labs and is assisting with the planning of the field tests. Special thanks are also extended to John Stanford and Scott Staples of BNSF for their support for the design and construction of the Large-Scale Test-bed as well as for their participation to the planning of the field tests.

REFERENCES


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Office of Research and Development
Federal Railroad Administration
Project Motivation

- CWR can break in cold weather and buckle in hot weather.
- Current difficulty to determine the rail NT *in-situ* leads to inefficient blanket-type slow-order mandates.

**TRAIN ACCIDENTS BY CAUSE FROM FORM FRA F 6180.54**

**MAJOR CAUSE= Track**

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<th>Type of Accident</th>
<th>Reportable Damage</th>
<th>Casualty</th>
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- Railroads can benefit from ability to measure rail NT *in-situ*.
- Buckling prevention particularly relevant to high-speed rail.
Previous methods for *in-situ* rail NT measurement

- **VERSE**
- **D’STRESEN**
- **MAPS-SFT**
- **OTHERS:** Ultrasonic Backscattering (U. Nebraska), Rayleigh Wave Polarization (Texas A&M U.)

**ALL HAVE PROS AND CONS!!**
Develop a wayside system for the measurement of rail NT with following features:

(1) NT measurement accuracy to within ± 5 °F.

(2) No need for reference value of stress.

(3) No sensitivity to rail supports or tie-to-tie variations.

(4) No need for calibration for different rail sizes/manufacturers.
Ultrasonic Guided Waves in rails

These simulations have helped identifying the correct guided wave mode and guided wave frequency for the rail NT measurement.
BNSF donated materials and know-how for design and construction of test-bed

Volpe participated with technical advice
The Large-scale Rail NT/Buckling Test-bed at UCSD (cont’d)

- 48 STRAIN GAGES
- Rail Heating System
- Thermal Test Protocol
- Thermal Camera

\[ \sigma = -\alpha E (T - T_N) \]
Provisional Patent Application filed by UCSD with USPTO in Nov 2011
Rail-NT Results from UCSD Large-scale Test-bed

Longitudinal Thermal Strain [μm/m]
Field Tests – TTC, Pueblo, CO, June 18-22

- **Rail-NT** prototypes at two locations: Concrete Ties and Wood Ties
- Rail size: 141 lb
- ISI Rail/BNSF monitored rail temperatures and forces at the two locations
Rail cutting and welding

- On Day 2 rail was cut at transition point to get zero-stress reference value to calibrate strain gages
- Rail was welded right after cutting
Force/Temp. from ISIRail sensors (days 2 & 3)

Concrete Ties

Wood Ties

Neutral Temperature points

Time
Results from **Rail-NT** system (concrete ties)

Conclusions: measurement from **Rail-NT** follows closely evolution of thermal force. Four NT points identified as four Minima in the Rail-NT curve with excellent accuracy.

<table>
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Accuracy: ±1°F

Accuracy: ±2°F
Results from **Rail-NT** system (wood ties)

Conclusions: measurement from **Rail-NT** follows closely evolution of thermal force. Four NT points identified as four Minima in the Rail-NT curve with excellent accuracy.

- Accuracy: ±1°F
- Accuracy: ±5°F
- Accuracy: ±2°F
- Accuracy: ±5°F
Conclusions

- **Rail-NT** – a system based on nonlinear ultrasonic guided waves - is being developed by UCSD and the FRA for *in-situ* rail NT measurement.

- Laboratory results at UCSD Large-Scale Rail NT/Buckling Test-bed indicate NT measurement accuracy of ±2 °F on 136-lb rail on wood ties.

- Field tests at TTC indicated rail NT measurement accuracy to within ±5 °F on 141-lb rail on both wood ties and concrete ties (no tie-to-tie variation effects).

- System performs well on both 136 lb rail (lab) and 141 lb rail (field).

- Field tests at TTC indicated that system is adversely affected by passing trains. Currently working on this aspect.
Acknowledgments

• Research at UCSD funded by FRA Grant FR-RRD-0009-10-01 (Mahmood Fateh, Program Manager)

• UCSD Large-Scale Rail NT/Buckling Test-bed:
  - former grad students Ivan Bartoli (now at Drexel Univ.), Salvatore Salamone (now at SUNY Buffalo)
  - BNSF (in-kind material donations, technical advice)

• Field tests at TTC:
  - BNSF (field test support, coordination)
  - ISIRail (force and temperature data collection)
  - Dave Reid (TTCI) (field test support, logistics)
  - John Choros (Volpe Center), Luis Maal (FRA) (test evaluation)