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Development of a Rail Stress Measurement System

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Summary

Engineering faculty and students in Transportation Technology Center, Inc.'s Affiliated Laboratory Program at Texas A&M have developed a prototype system for proof of concept evaluations used to measure rail longitudinal stress on track while stationary. The system generates vibrations in the rails and uses the polarization of Rayleigh surface waves as the measure of longitudinal stress. The railways wish to manage rail longitudinal stress to prevent buckling and rail fracture due to high tensile forces. Ultimately, the rail stress measurement system should be capable of measuring in-motion while traveling down the railway. In the final proposed configuration, the experimental procedure will use a pulse laser to generate ultrasonic waves in a rail and two laser Doppler vibrometers (LDVs) to measure both the in-plane and out-of-plane velocity components of a Rayleigh wave as a function of the longitudinal stress. This provides a noncontact excitation and a noncontact detection of the ultrasonic waves; thus, it makes it possible to implement it in an in-motion system. A prototype of the rail stress measurement cart was developed using the proposed configuration. It is currently undergoing tests at an outdoor test facility.

Previous analytical and laboratory work developed and proved the concept of using Rayleigh surface wave polarization to determine rail longitudinal stress. Initial field trials with the prototype have shown there are some implementation issues to resolve with on-track measurement in the railroad environment. Some of these issues are:

- Track gage and rail shape tolerances will require adjustments to the LDV alignment as the system proceeds down the track.
- Vibrations of the in-motion system will generate additional noise, which could adversely affect the measurements.
- Ambient temperature and humidity changes could affect the accuracy and precision of the instrumentation.
- Rail surface condition must be considered, as surface degradation and/or grease may affect the accuracy of the measurements.

INTRODUCTION

The practice of installing continuous welded rail (CWR) in the United States has been increasing since it first began in the 1930 so that now a high percentage of heavily used main line track is CWR. This has occurred because the elimination of joints prevents the occurrence of many types of flaws such as broken joint bars and bolt hole cracks, requires less maintenance, and provides a smoother ride with lower impact for rolling stock and their passengers or lading.

However, these exceptionally long members react to thermal expansion or contraction as members with fixed ends, causing compressive stress in warmer temperatures and tensile stress in colder temperatures. The expansion and contraction of the rails is controlled by specialized rail anchors or by the resistance to longitudinal movement provided by elastic fasteners, and all railroads have continuous welded rail plans approved by the Federal Railroad Administration.

For newly and properly installed rail, longitudinal forces large enough to buckle track are highly unlikely; however, as tracks shift during service usage, these high longitudinal forces can become a reality. Sometimes, these thermal loads alone can induce a static buckling, but more often thermal buckling is precipitated by a vehicle load on the rail. Figure 1 shows a track buckle.

Figure 1: Track Buckle[1]

As indicated in this technology digest, the railroads are continually seeking better ways to manage CWR in order to further reduce the occurrence of buckled track derailments, especially because buckled track can occur suddenly and is difficult to predict.

Current Methods

Railroads manage CWR safely by following their CWR plans, which include visual inspection by inspectors especially qualified (under 49CFR213.7(c)) to note signs that rail is under unusual stress. In some specialized cases, railroads monitor longitudinal forces by making use of strain gages installed on rails determined to be at a high risk of buckling. While effective, these methods require a calibration of the strain gages with zero force in the rail, which is difficult and time consuming at any point after rail installation. Typically, this calibration is accomplished by unclipping and cutting the rail to relieve longitudinal stress, installing strain gages, and then re-welding the rail. While effective in rails that must be cut as a part of rail maintenance, cutting the rails for the sole purpose of calibrating strain gages is destructive and labor intensive, and it adds a future weak point with a thermite weld.

Consequently, much research has gone into improving rail stress measurement. One updated method involves drilling a small, shallow hole in the rail and applying a system of three strain gages around the opening, rather than cutting an entire section of rail. However, holes must be drilled in multiple locations in order to obtain an adequate reading. This method shows marked improvement over traditional methods in accuracy and is minimally invasive; however, it remains labor intensive and requires track closures.

The rail uplift technique allows for absolute force calibration of strain gages without cutting the rail. This involves unclipping the rail and applying a vertical force through the use of a modified rail car. By measuring the deflections under a fixed uplift load (or the uplift load required for a fixed vertical deflection), the longitudinal force for a given section of rail can be determined, thereby allowing strain gage calibration without rail cutting.[1]

The vertical rail stiffness equipment (VERSE) method is another uplift technique used to measure the longitudinal loads in rails. A mobile jack frame exerts an uplift load of 2.25 kips (10 kN) while the load and displacement is tracked by transducers and relayed to a handheld computer that can then calculate the rail neutral temperature (RNT), that is, the temperature for which a rail experiences no longitudinal stress.[2] Due to the variability of rail neutral temperature and the time required to make a measurement, these spot measurement methods are not widely used in the railroad industry.

Additional methods involve the application of lateral vibrations to determine the lateral bending wave number of the rail or an examination of the Electro Mechanical Impedance (EMI) behavior to determine rail stress. However, these methods have proven ineffective outside of a laboratory setting.

Rayleigh Wave

A Rayleigh wave particle has an elliptical motion that is retrograde compared to the direction of the wave propagation. Thus, a wave travelling to the right will induce a counterclockwise motion in individual particles (Figure 2).

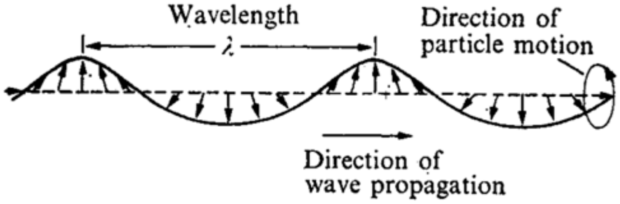

Figure 2: Rayleigh Wave Particle Motion[3]

The Rayleigh wave expends almost all of its energy propagating along the surface and thus is an ideal excitation mechanism to measure surface stress. It is slower than both the shear and longitudinal waves, and its wave speed is independent of wave number (and thereby wavelength), which makes it nondispersive.

The motion within a Rayleigh wave can be described by its polarization, which is defined as the ratio of maximum in-plane displacement to maximum out-of-plane displacement of a particle on the surface. For real media, Graff states that the out-of-plane displacement is always greater than the in-plane displacement, typically 1.5 times greater, and it yields a polarization value of around 0.67.[3] The polarization of the Rayleigh wave is an order of magnitude more sensitive than the Rayleigh wave speed. Thus, this research explores the method of measuring longitudinal rail stress using Rayleigh wave polarization (a technique proven effective in a controlled laboratory environment) and evaluates its practicality for in-field testing.

EXPERIMENTAL SETUP

The experimental setup consists of an arbitrary function generator that generates a 10 burst sine wave with a peak-to-peak amplitude of 1 volt. This signal is magnified with a radio frequency amplifier before being sent to a wedge transducer, which transfers the excitations signal to the rail. In-plane and out-of-plane velocities are detected further down the rail by a pair of laser Doppler vibrometers (LDVs) and then digitized by an oscilloscope. The data is transferred to a computer via Ethernet, and finally processed in Matlab to obtain the Rayleigh wave polarization. In order to simulate the stress of a segment of continuous welded rail at a high temperature, a compressive load is applied to the rail segment using a hydraulic jack. This experimental laboratory setup is shown in Figure 3.

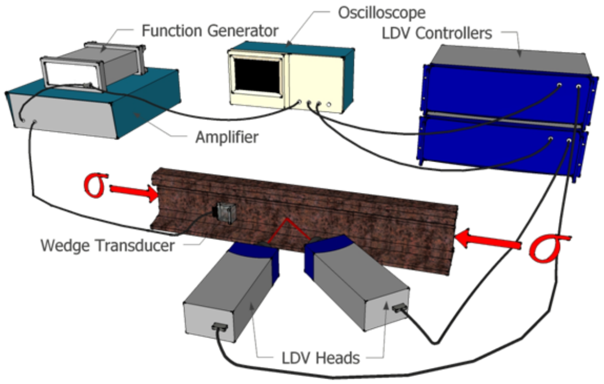

Figure 3: Measuring Rail Stress using Rayleigh Waves

Results from laboratory testing of short pieces (i.e., 5 feet in length) of rail in tension and compression have been encouraging. The measurement method is equally successful for rail in tension or compression.[4]

TEST BED

In order to determine the practicality of this method for in-field testing, a test bed was constructed. It consists of a 40-foot long track panel with concrete ties and header beams. The header beams are connected with DYWIDAG bars. The stressing is performed with a 100-ton jack and a hand pump. The rails can be stressed to a maximum force of 50 tons if the cylinder acts in the center of the header beams. Strain gages were installed at the neutral axis of the rail to measure the actual strain. The strain gage data serves as a benchmark to compare to the stress measurements. Figures 4 shows the in-field test bed.

Figure 4: Test Bed

PROTOTYPE DEVELOPMENT

The first step toward a fully mobile rail stress measurement apparatus is a direct adaptation of these measurement techniques to a stop-and-go system. To this end, a prototype stress measurement cart has been developed. The biggest change from the laboratory setup to an in-situ setup is the noncontact Rayleigh wave excitation. By replacing the wedge transducer used in the laboratory with a pulse laser, the measurement process has become fully noncontact. Not only is this upgrade required for the future use of a moving rail stress measurement system, but it also significantly speeds up the stop-and-go system. The noncontact excitation provided by the pulse laser avoids reattaching the wedge transducer at every measurement location.

The other end of this fully noncontact stress measurement technique is managed by the two LDV heads.

To aid in transporting the cart to measurement sites, it has been designed to be capable of traveling on and off the tracks. The primary rear axle, located beneath the main instrumentation cabinet, is a standard 5-foot trailer axle with pneumatic wheels. These tires help support the back of the cart whether on or off the tracks, and help cushion any bumping or jostling that could damage the equipment.

The cart is designed to transfer to the track at railroad crossings. The cart has a towing connection for use with high-rail vehicles, which eliminates the need to manually move the cart. Because the hitch height of high-rail vehicles varies, an articulated trailer hitch was chosen to allow for free rotation about all three axes of the hitch and to accommodate any hitch height.

While a significant amount of effort went into designing the measurement apparatus, it was recognized that modifications may become necessary. For this reason, Bosch aluminum framing was chosen to make up the structure of the cart.

Most of the instrumentation used in the experimental setup is designed for the low-dust, low-moisture environment of a laboratory. To increase the lifespan of this equipment in a field environment, the instruments are stored in enclosed housings constructed from water resistant, film faced plywood secured into the channels of the framing members with weather stripping.

In total, there are three instrument housing units. The largest unit, located at the rear of the cart, contains a pair of 19-inch, 20 RU (35-inch tall) rack cabinets that hold the oscilloscope, the two LDV controllers, the neodymium-doped yttrium aluminum garnet; Nd:Y3Al5O12 (Nd:YAG) power supply unit, and the Helium-Neon (HeNe) alignment laser controller. The second housing unit contains the Nd:YAG and HeNe laser heads. These laser heads are accessed from the side of the cart. From this opening, the mirrors that control the direction of the excitation beam can be adjusted. The final instrument enclosure houses the LDV heads and their associated hardware.

The process of conducting rail stress measurements would be expedited if all inputs and common adjustments could be performed from a single location on the cart. To facilitate this, the LDV heads have been affixed to a motorized translation stage with a 2-inch travel distance with a control unit located in the main instrument cabinet. Additionally, a webcam has been placed between the LDV heads so that the necessary adjustments can be monitored from the same location. Once the measurement process has begun, any measurements performed along a stretch of track clear of obstructions can be completely monitored and controlled from this location. Figure 5 shows the prototype rail stress measurement system cart.

Figure 5: Prototype Rail Stress Measurement System Cart

Moving from a stop-and-go measurement system to an in-motion system has several challenges. Some of these arise due to the movement of the measurement device. Obviously, the vibrations of the in-motion system generate additional noise, which could adversely affect the measurements. However, track gage and rail shape tolerances introduce additional challenges, as adjustments to the laser alignment must be made as the system proceeds down the track. Laser alignment is critical in the measurement of in- and out-of-plane displacements of the Rayleigh wave. Vibration control and video triangulation should nullify these issues.

Finally, challenges also arise as the prototype is taken from the laboratory into the field. Not only must the LDV heads comply with rail clearance restrictions, but ambient temperature and humidity changes could affect the accuracy and precision of the instrumentation. Researchers are currently working with the LDV manufacturer on this issue. Also, rail surface condition must be considered, as surface degradation and/or grease may affect the accuracy of the measurements.

The current field tests are aimed at identifying and mitigating the implementation issues. Initial tests have shown significant variability in results which are believed to be related to test boundary conditions and the ability of noncontacting transducers to produce sufficient signal clarity.

CONCLUSIONS

This research has led to the development of a longitudinal rail stress measurement apparatus prototype for use in the field. This prototype measures stress by analyzing the Rayleigh wave polarization which is recorded by a pair of LDVs. After conducting laboratory experiments, a prototype and a test bed were designed and constructed. The cart prototype will enable measurements previously carried out only in the laboratory to be performed in the field, which will allow rails to be monitored more frequently and improve the overall safety of the railroads.

FUTURE WORK

More comprehensive field testing, with track panels and longer track segments will be conducted to better determine the capabilities of the measurement system. An implementation feasibility report will be issued.

ACKNOWLEDGEMENTS

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