ABSTRACT

Track performance and maintenance requirements are strongly related to track modulus – the ratio between the rail deflection and the vertical contact pressure between the rail base and track foundation. This work seeks to develop an on-board, real-time, non-contact track modulus measurement system that functions at track speed.

Measuring track modulus from a moving rail car is nontrivial because there is no stable reference for the measurements. The proposed system is based on measurements of the relative displacement between the track and the wheel/rail contact point. A laser-based vision system is used to measure this relative displacement. Then a mathematical model is used to estimate track modulus.

This paper addresses new findings as a continuation of the University of Nebraska-Lincoln and Federal Railroad Administration research presented at AREMA 2005. These new findings include recent system upgrades and hundreds of miles of new test results from revenue service. System upgrades include a new passive loading vehicle, a simplified calibration system, and the real-time processing of data. Results are presented from field testing in revenue service at different locations, on various types of track, and in different weather seasons. In addition, the effect of speed is analyzed and special track transitions (bridges, road crossings, switches) are discussed.

BACKGROUND

Railroad safety is highly dependent on track quality. Track modulus is one of many accepted Indicators of the quality and safety of railroad track. Modulus can be defined as the supporting force per unit length of rail per unit deflection [1]. Track modulus is influenced by many factors such as the quality of rails, ties, rail joints, ballast, and sub-grade. Modern rail systems traveling at higher speeds require somewhat stiffer and more uniform track.

Traditionally, determining track modulus has been a difficult task. It involved a work crew traveling to a section of track with special equipment to apply known loads and measure the resulting deflection. Yet this expensive and cumbersome process yielded knowledge of modulus for only limited locations.

In the recent past, various attempts at measurement of track modulus from a moving railcar proved to be difficult since the moving car provides no absolute frame of reference for the measurement. The measurement system presented in this paper estimates modulus by measuring the relative displacement between the wheel/rail contact point and the rail some distance from the contact point. Deflection of the track is caused by the weight of the railcar. A heavy car on soft track will “sink” into the track. The measurement system uses analytical models of both the railcar and the track to estimate track stiffness based on these deflection measurements.

THE MEASUREMENT APPROACH

The measurement system estimates track modulus by measuring the deflection of the rail relative to the railcar. The modulus is then estimated using an analytical expression, called the Winkler model, which relates the deflected shape of the rail to the applied loads [2].
The system is a non-contact measurement sensor that uses two line lasers and a camera mounted to the railcar truck, Figure 1. As seen from the camera view (Figure 1, right), each laser generates a curve across the rail head. The exact shape of the curve depends on the shape of the rail. The distance, $d$, between the curves is found using imaging software. The change in the distance $d$, as the car moves along the track represents a change in the relative displacement between the railcar truck and the track (assuming the shape of the rail and applied loads is constant). Therefore, as the distance between the camera and rail decreases, the measured distance, $d$, will also decrease. The opposite is also true, as the distance between the camera and rail increases, the measured distance, $d$, will increase. Two lasers are used to increase the resolution of the measurement system and the overall sensitivity of the instrument.

![Figure 1. The Measurement Approach](image)

**ANALYTICAL MODEL**

The measurements obtained from this system are mapped into an estimate of track modulus using an analytical model of the track and the geometry of the system.

**Track Model**

The model used here is referred to as the Winkler model [3]. The vertical deflection, $y$, for a given point load, $P$, as a function of the distance from the load, $x$, is defined as follows:

$$\frac{P\beta}{2u}e^{-\beta x}\left[\cos(\beta x)+\sin(\beta x)\right] \quad (1)$$

where:

$$\beta = \left(\frac{u}{4EI}\right)^{\frac{1}{2}} \quad (2)$$

Here, $E$ is the modulus of elasticity of the beam (i.e. rail) and $I$ is the second moment of area of the beam. The variable, $u$, is the estimate of the track modulus. This model linearly relates rail deflection to a single applied point load and has a non-linear relationship to track modulus. Rail deflection under a planar (for each track) railcar is calculated with the Winkler model using the superposition of four point loads at each wheel contact point.

**System Model**

The system model relates the measured distance between the lasers to the track modulus. The rail deflection measured by the sensor is dependent on these four wheel loads. The sensor will measure the relative rail displacement between the rail and wheel/rail contact point. This measurement can be made if it is assumed that the instrument beam, truck, and wheels are rigid. With this assumption, the distance between the sensor system and wheel/rail contact point can be assumed constant. Only rotation of the truck will cause this distance to change, but this rotation can be measured and corrected.

Error! Reference source not found. illustrates that the fixed distance between the wheel/rail contact point and sensor, $H$, relates the relative rail displacement, $y_r$, to the measured height of the sensor above the rail surface, $h$. Here $y_{\text{camera}}$ is the deflection of the rail at the location underneath the camera/lasers.
and $y_{\text{wheel}}$ is the deflection of the rail at the wheel nearest the sensor. These rail deflections are calculated using the Winkler model and superposing the deflections caused by each of the four wheel loads. The deflections are negative in value because the positive axis is defined upwards.

The sensor reading, which is the measured distance between the lasers, is geometrically related to the height of the sensor above the rail. The sensor in effect measures its height above the rail by measuring the distance between the lasers. As the sensor moves closer or farther from the rail surface the distance between the laser lines changes. Figure 3 is a schematic of the sensor.

![Figure 2. Rail Deflection/Sensor Measurement](image1)
![Figure 3. Sensor Geometry](image2)

From Figure 3 the following equations can be written:

\[(L_1 + l_1)\tan \theta_1 = h \]  
\[(L_2 + l_2)\tan \theta_2 = h \]  
\[d = l_1 + l_2 \]

where $L_1$ and $L_2$ are the horizontal displacement of the lasers from the camera, $\theta_1$ and $\theta_2$ are the angles between the lasers and the horizontal, $l_1$ and $l_2$ are the horizontal distance between the center of the camera and laser/rail intersection, $h$ is the vertical distance between the camera/lasers and the surface of the rail, and $d$ is the distance between the lasers on the rail surface. Solving these equations results in:

\[d = \frac{h}{\tan \theta_1} + \frac{h}{\tan \theta_2} - (L_1 + L_2) \]

Using equations (6) a sensor reading can be calculated for a value of track modulus [3].

**FIELD TESTING**

The system used in field testing is shown in Figure 4. The system consists of a refurbished caboose and hopper car donated by the Union Pacific Railroad. The caboose serves as the crew platform and contains computers and recording equipment to process data. The caboose uses geospatial mapping software along with a wheel odometer and GPS system (2m RMS error) to document the location of the data. The hopper car has two red beams mounted to the side frames of the trailing truck (inset, Figure 4). The beams are bolted to the side frames without modification of the side frames. The beams hold the sensor head that contains the camera and lasers as shown in Figure 1. This system has now been used in over 500 miles of revenue service testing and the data statistically analyzed.
An example two different one mile sections of data are shown in Figures 5 and 6. In Figure 5, the plot shows the relative displacement of the rail, $h$ (as defined in Figure 2), as a function of GPS coordinates given in degrees of longitude and latitude. A satellite image (from Google Earth, [4]) is overlaid on the data. Similarly, in Figure 6, it possible to qualitatively trace changes relative displacement to specific track events such as at grade road crossings, culverts, and bridges.

Figure 5. Relative displacement vs. location

Figure 6. Relative displacement vs. location
In Figure 6, individual data points are spaced approximately every twelve inches. Soft sections of track are seen at the approaches to a grade crossing at approximately mile post 38.8 and a bridge at approximately mile post 38.6. These data have been collected over many miles of revenue service and then have been analyzed. One way to use the data is to analyze specific sections of track.

An example of a typical image from a sensor reading is shown in Figure 7. This image shows the aerial view of a 5-span bridge location and the top of rail as viewed by the measurement camera. Both the field and flange edges of the rail are visible and the laser lines appear as curves as they cross and intersect the rail surface (as in Figure 1). The local GPS, odometry, time, and speed readings are interlaced with the image. Image processing software is then used to determine the minimum distance between the laser lines and this is then translated into displacement readings and finally into an estimate of the modulus.

Figure 7. Aerial view of the location of a 5-span bridge with GPS coordinates superposed and the laser image inset.

Figure 8 illustrates an example of trending. Figure 8a) is a plot of relative displacement, \( h \), versus milepost for a test run during October 2005. The solid red line is the mean value of \( h \) over the interval shown, while the dashed red lines are one standard deviation either side of the mean. There are two significant dips below 11.8 in. These dips are the relatively soft approaches to the bridge abutments. The two high peaks adjacent to the dips are the stiff bridge abutments, and one can actually count four peaks in between that represent the intermediate bridge piers.

Figure 8b) shows the same location in January 2006, approximately 3 months later. Note that the shape of the plot and the magnitude of the peaks and dips are essentially the same relative the means. The mean values for the plots are differ by approximately 0.2 in. (about 11.8 in. versus about 12.0 in.). This is due to using a slightly different setup height for the camera. The conclusion based on the nearly identical shape of these two plots is that there was little change in track condition over the 3-month time interval.
The next example is also of a bridge. However, in this case a significant change occurred during the three months between testing. From Figure 9 one can see that the deflection of the soft approach has increased from about 0.4 in. to about 0.6 in. over the three month time interval. The conclusion is that this bridge approach is deteriorating quickly and should be considered for maintenance.

Figure 9. A Bridge with a degrading approach.

Figure 10 illustrates the effect of track maintenance. A high speed crossover, or turnout, was improved dramatically during the time interval between our test runs. Railroad personnel recognized this problem visually before the second test and performed scheduled maintenance. These plots clearly show that regular maintenance can make a significant difference in track modulus.

Figure 10. A high speed crossover (turnout) improved by maintenance
CONCLUSIONS

The measurement system can make real-time measurements of the vertical track deflection directly, and track modulus indirectly, from a moving railcar. These examples of displacement and modulus data suggest such information could be used to better plan track maintenance cycles. Future work will include further long-distance testing on revenue track, trending these data over time, and development of a defect rating system.

ACKNOWLEDGMENTS

This work is being performed by Dr. Shane Farritor, Dr. Richard Arnold, and Sheng Lu, Brian McVey, Cory Hogan, and Chris Norman of the University of Nebraska-Lincoln under grant from the FRA. Mahmood Fateh and Dr. Magdy El-Sibaie of the FRA’s Track Research Division have provided technical support and direction. Special Thanks to UPRR for donations of rolling stock. Also, special thanks to both UPRR and BNSF for on-going support of this project, especially in the form of operational support and track access for testing. Data shown are from BNSF’s Creston Sub in the Lincoln Division.

REFERENCES