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Real-Time Vertical Track Modulus Measurement System from a Moving Railcar

SUMMARY

Track modulus is a measure of vertical roadbed stiffness and is an important parameter in track quality and performance. Modulus is defined by the ratio of rail deflection to the vertical contact pressure between rail base and track foundation. This project is to develop a system for on-board, real-time, non-contact measurement of track modulus. A major challenge in measuring track modulus from a moving rail car has been the lack of 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 was developed to measure this relative displacement and a mathematical model was used to estimate track modulus from the relative displacement. Analysis and dynamic simulations of a moving car were performed to evaluate the design and sensitivity of the proposed system and to demonstrate the effectiveness of the system. Results of preliminary field tests for a slow (<10 mph) moving railcar over various sections of track, including road crossings, rail joints, and bridges, showed excellent agreement with independent way-side measurements.

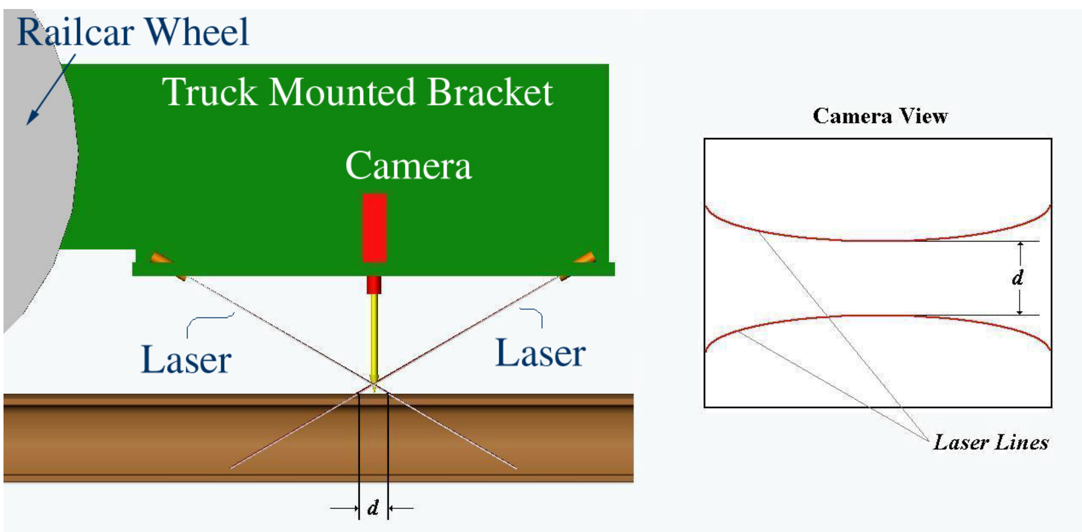

Figure 1. The Proposed Approach

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 relatively 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 proposed system estimates modulus by measuring the relative displacement between the wheel/rail contact point and the rail. Deflection of the track is caused by the weight of the railcar. A heavy car on soft track will “sink” into the track. The proposed system uses analytical models of both the railcar and the track to estimate track stiffness based on these deflection measurements.

THE PROPOSED APPROACH

The proposed 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 shape of the rail to the applied loads [2].

The proposed 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), 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 train 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.

ANALYTICAL MODEL

The measurements created by 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:

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

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

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 mathematical 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 taken into account and corrected.

Figure 2 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_{camera} is the deflection of the rail at the location underneath the camera/lasers and y_{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.

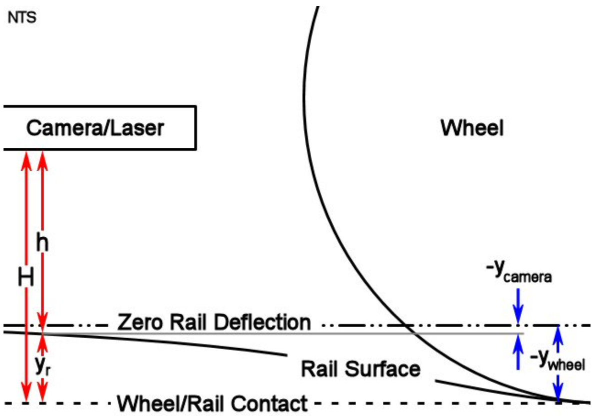

Figure 2. Rail Deflection/Sensor Measurement

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 lasers changes. Below is a schematic of the sensor (Figure 3).

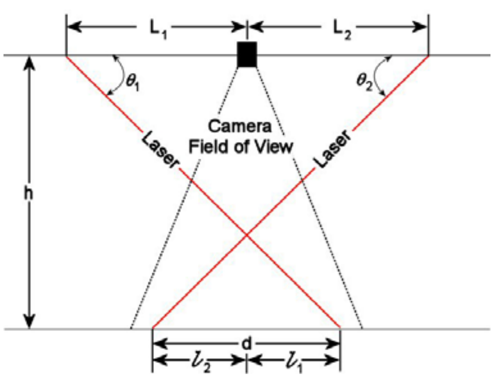

Figure 3. Sensor Geometry

From the above figure the following equations can be written:

$$(L_1 + l_1)\tan\theta_1 = h \qquad \text{Equation 1}$$

$$(L_2 + l_2)\tan\theta_2 = h \qquad \text{Equation 2}$$

$$d = l_1 + l_2 \qquad \text{Equation 3}$$

Where L_1 and L_2 are the horizontal distances of the lasers from the camera, θ_1 and θ_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 two projected lasers lines on the rail surface. Solving these equations results in:

$$d = \frac{h}{\tan\theta_1} + \frac{h}{\tan\theta_2} - (L_1 + L_2) \qquad \text{Equation 4}$$

Using Equations 1-4, 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.

Figure 4. UNL/FRA Track Safety Research Vehicle

An example of a typical image from a sensor reading is shown in Figure 5. This image shows 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, odometer, time, and velocity readings are interlaced with the image. Software is then used to determine the minimum distance between the laser lines. This is then translated into displacement readings and finally into an estimate of the modulus.

An example of one mile of data is shown in Figure 6. 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. In this figure it possible to qualitatively trace changes relative displacement to specific track events such as at grade road crossings, culverts, and bridges.

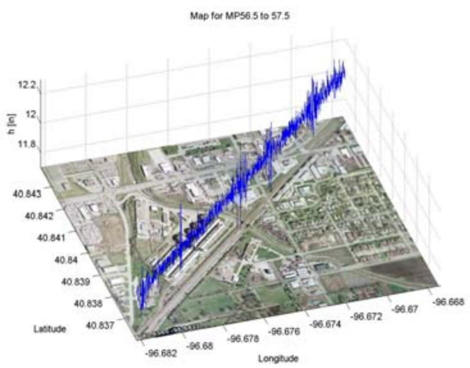

Figure 5. Relative displacement vs. location

This data has been collected over many miles of revenue service Class IV track and then has been statistically analyzed.

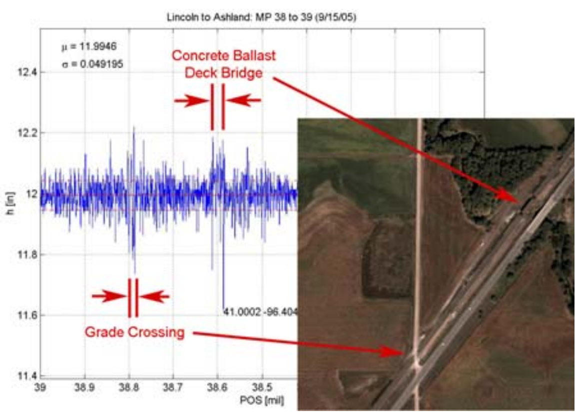

Figure 6. Displacement vs. location

One way to use the data is to analyze specific sections of track. 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.

CONCLUSIONS

A system is proposed to make real-time measurements of the vertical track modulus from a moving railcar. The basic concept is explained and some field tests are presented. 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 and trending this data over time.

ACKNOWLEDGMENTS

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[4] http://maps.google.com/

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