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A Preliminary Design of a System to Measure Vertical Track Modulus from a Moving Railcar

SUMMARY

Track modulus is a measure of its 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 intends to develop a system for on-board, real-time, non-contact measurement of track modulus. A major difficulty 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.

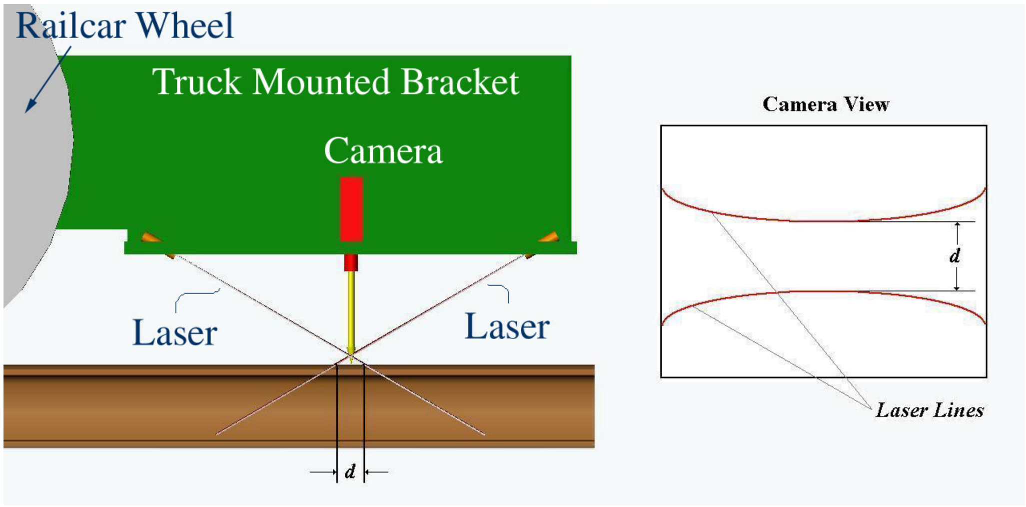

Figure 1. The Proposed Approach.

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 is defined as the coefficient of proportionality between the rail and the vertical contact pressure between the rail base and track foundation [1]. More simply, it is the supporting force per unit length of rail per unit deflection [2]. 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 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 that relates the shape of the rail to the applied loads. The model used is referred to as the Winkler model [3].

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.

The stated approach is based on some fundamental assumptions. First, that the Winkler model is an accurate prediction of rail shape. Or, more precisely, that the Winkler model has high resolution and can accurately predict relative changes in track modulus. A second assumption is that there are no dramatic changes in the shape of the rail head over the distances where relative measurements are taken. Also, that the applied load is constant between two measurements. Dynamic loads (bouncing of the car) can affect this assumption. However, the simulation below suggests that changes in applied loads should be less than 14%, which leads to reasonably accurate measurements. The final assumption is that the wheel/truck system is rigid. This assumption does not include the car’s suspension. The validity of the approach is being evaluated in both simulation and in field tests.

ANALYTIAL MODEL AND SIMULATION RESULTS

The proposed measurement system was evaluated in simulation. Analytical models were created for a railcar, the track, and the sensor system as described below.

Railcar Model

A simple model of a rail car was created to determine the motion of the car and trucks moving over various track conditions. A free body diagram of the model is shown in Figure 2. This model determines the wheel/track contact forces that are important to the Winkler track model. The car and trucks were modeled as rigid masses with moments of inertia. The entire car translates down the track. A spring and damper connect the car and each truck. Each mass has two degrees of freedom: a rotation and a vertical displacement. Each truck interacts with the rail through the wheels, which are considered rigid. The interaction between the wheels and the rail is considered to be rigid.

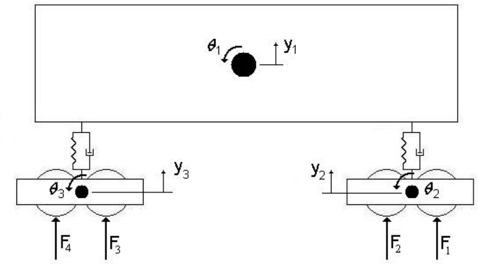

Figure 2. Railcar Model.

Track Model

The model used here is referred to as the Winkler model [3]. It is a continuum mechanics model for a point load applied to an infinitely long elastic beam mounted on an elastic foundation. The applied load is perpendicular to the length of the beam (i.e. vertical).

The vertical deflection, y, for a given point load, P, as a function of the distance from the load, x, is defined as follows:

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

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 railcar is calculated with the Winkler model using the superposition of four point loads at each wheel contact point. Figure 3 shows the results of this model. Here the deflection of the rail relative to the wheel/rail contact point is shown for a fully loaded coal hopper for various track moduli.

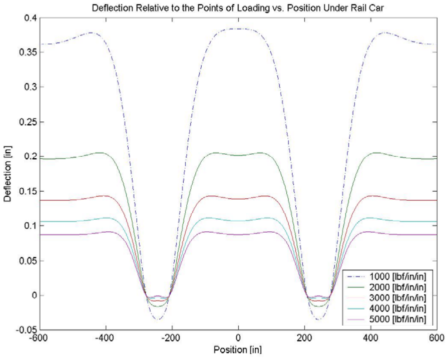

Figure 3. Rail Deflection Relative to the Wheel/Rail Contact Point for a coal hopper.

This model has been verified using trackside deflection measurements (Figure 4.) A four-foot stake is driven into the sub-ballast near the rail to provide a stable reference and a displacement transducer (LVDT) measures the displacement of the rail as a car of known weight moves slowly (at known speed) past the measurement point.

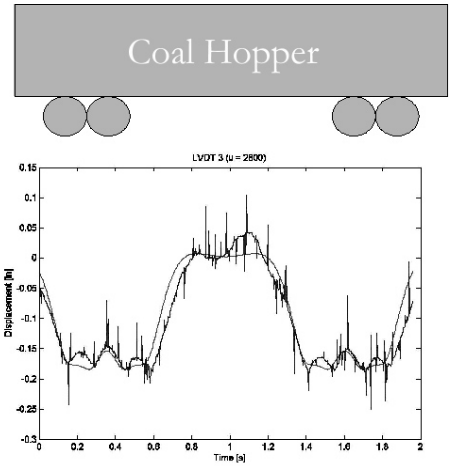

Figure 4. Track side displacement measurements and model fit.

Figure 4 shows one such track-side measurement with a fit of the above model superimposed. It can be seen that the model accurately predicts the track deflection. To make the fit, the model uses a modulus value of 2800 psi. This type of measurement is being used to verify the performance of the on-board system presented in this paper.

FIELD TESTING

Field tests have been conducted on-board a moving railcar at slow speeds (< 10 mph). A system has been constructed and mounted on a loaded coal hopper with a weight of approximately 65,000 lbs per axle (Figure 5.) The system consists of a steel beam (gray in Figure 5) that is bolted to the top of the sideframe of the leading truck. The beam extends beyond the sideframe and is used to hold the two line lasers and camera. Neither the sideframe nor any other part of the railcar was modified and the system can be installed in the field.

Figure 5. Field System on a coal hopper.

A series of four typical images taken from the on-board camera are shown in Figure 6. These images are taken on a section of class three track. Again, the camera is looking down at the railhead and the two line lasers can be clearly identified. The distance between the laser curves represents the relative deflection between the top of rail and the wheel/rail contact point. The numbers in the image represent an odometer reading, in feet, of the distance traveled along the track. It can be seen in Figure 6 that the distance between the laser lines changes dramatically over 15 feet. This corresponds to a change in modulus over that short distance. This change has been verified using the trackside measurements (e.g. Figure 4).

Figure 6. Four typical measurements.

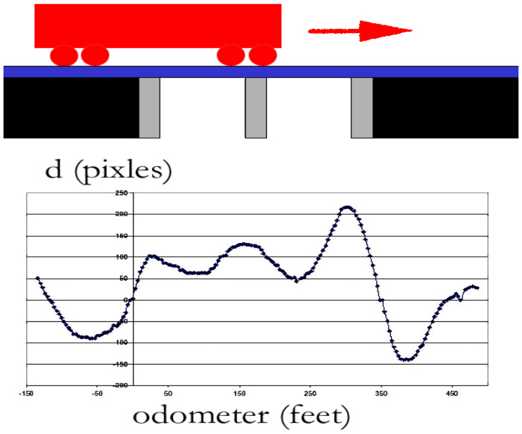

Figure 7. Bridge Crossing.

Figure 7 shows these measurements as the on-board system passes over an open-deck bridge. The top of Figure 7 shows a schematic of the bridge that has two abutments and a support in the center of the span. The bottom of the figure shows a plot of the distance between the laser lines as a function of the distance traveled along the track. This graph suggests that the approaches on both sides of the bridge are very soft and the stiffer abutments and supports can be clearly identified.

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. The results of these initial tests indicate that the system can make useful measurements that could be the basis for continuous computation of modulus as the railcar moves along the track.

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FOR FURTHER RESEARCH

The current phase of work is focused on further verification of the measurements using independent track-side measurements of modulus. A more robust system will be developed based on this concept and will be tested for longer distances on a wider variety of track. Planned future work also includes calibration and dynamic effects at higher speeds.

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