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FEASIBILITY OF TRACK ENERGY METRIC

SUMMARY

Identifying track locations with rapid degradation potential and derailment risks due to structural failure is important for the railroad industry. Among the tools used to identify degradation are Track Quality Indexes (TQIs), a track geometry-based metric to characterize overall track quality. However, TQIs generally do not reflect the effect of short wavelength events, such as poor rail joints, or considerations required for long wavelength track features such as curves. Additionally, TQIs do not reflect vehicle-track interaction (VTI) and the potential damage to rolling stock components. Therefore, a metric that identifies track areas of concern by appropriately capturing the effects of a wide range of defect wavelengths and potential VTI forces would benefit the railroad industry.

From June 2016 to June 2017, the Federal Railroad Administration (FRA) sponsored a study, executed by ENSCO, to develop a track energy metric (TEM). The method is based on the hypothesis that track locations with higher energy transfer rates between vehicle and track correspond to locations with higher track degradation rates. A portion of these locations could also translate into higher rolling stock component degradation rates. The formulation of the proposed metric is intended to capture information from a broad range of track wavelengths as well as VTI.

Simplified dynamic models were used to develop a TEM formulation in the vertical direction only using acceleration, mass, and the conservation of energy law. Simulation results showed good agreement between theoretical TEM calculations and computer simulation derived values for contact force and energy transfer into track.

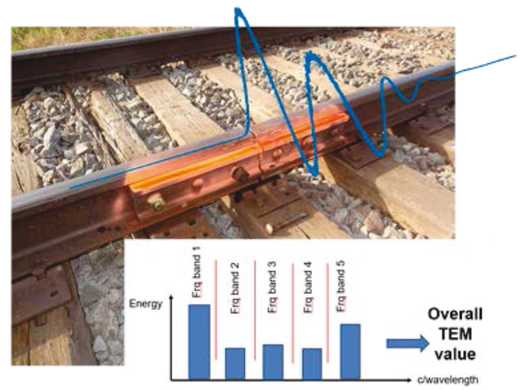

Figure 1. Concept of Track Energy Metric for Characterizing Track Quality

This study indicated that the TEM formulation could effectively reflect mechanical energy transferred into a track in the vertical direction and hence identify locations with potential high track degradation rates. However, this study would have to be further expanded to generalize the TEM formulation to account for and assess its accuracy in the lateral direction as well as the effects of energy dissipation.

BACKGROUND

As rail vehicles traverse track structures, energy is transferred from the vehicle to the track. The amount of transferred energy depends on many conditions including, but not limited to, deviations in track geometry, corrugation, impacts at misaligned joints, horizontal curvature, and rolling stock condition. The hypothesis of this work is that locations with "high" energy transfer between track and moving vehicles can turn into locations with relatively high potential for degradation and high derailment risk due to structural failure.

The total energy input to the track from dynamic contact forces due to track irregularities can be categorized as: 1) Recoverable energy associated with elasticity of the track and its components, 2) Dissipated energy associated with damping characteristic of the track and its components, and 3) Dissipated energy that does not cause direct damage to the track and its components (e.g., portion of energy associated with sound or radiated heat). After a long enough time interval, recoverable energy will also be dissipated in the track components. All the dissipated energy contributes to increase of entropy of the track structure system. By disregarding the dissipated energy as radiated heat or sound compared to the dissipated energy in the track components, the input energy into track could be a measure of damage to track.

An approach that is able to quantify energy transfer from a moving vehicle to the track could lead to a metric that can characterize track differently than traditional means. Such a metric, referred to as the Track Energy Metric (TEM), could capture information from various deviations with a broader wavelength range when compared to traditional TQIs and could identify energy content due to specific conditions that might lead to an informed decision on what to address in the track.

OBJECTIVES

The objective of this preliminary study was to develop an approach for an energy-based method to characterize track quality, evaluate its feasibility and effectiveness based on computer simulations, and to determine whether the approach effectively estimated the amount of energy transferred into track in the vertical direction.

METHODS

To quantify energy transfer from a moving vehicle into a track, the dynamic interaction of the rail vehicle with different irregularities in track needed to be understood. To this end, the theoretical track perturbations were studied and three different theoretical track layouts were modeled representing various irregularities with a range of wavelengths. Next, simple two and three Degree-of-Freedom (DoF) dynamic models of a single wheel interacting with track in the vertical direction were employed to study the physics of the energy transfer and to derive the formulation of the TEM. Finally, the TEM formulation was assessed using more comprehensive dynamic models using VAMPIRE® simulation software for a locomotive and a loaded/empty hopper car.

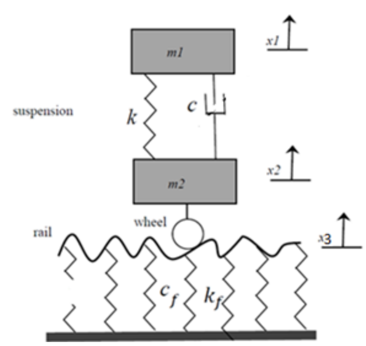

Figure 2. Simple Three DoF Model Representing Sprung, Unsprung, and Rail Masses

As shown in Figure 2, the three DoF model includes sprung (m_1), unsprung (m_2), and rail masses (m_3). It also has suspension components, wheel-rail interaction based on Hertz theory, and a soft foundation for track. The dynamic equations of motion for the illustrated system in Figure 2 are:

$$\begin{cases} m_1(\ddot{x}_1 + g) + k(x_1 - x_2) + c(\dot{x}_1 - \dot{x}_2) = 0 \\ m_2(\ddot{x}_2 + g) + k(x_2 - x_1) + c(\dot{x}_2 - \dot{x}_1) = F \\ m_3(\ddot{x}_3 + g) + k_f(x_3) + c_f(\dot{x}_3) = -F \end{cases}$$

Where F is the normal contact force at the interface between wheel and rail and is formulated based on Hertz Theory.

In order to estimate the energy transfer into the track, the energy content of all the model's components was obtained by expressing the kinetic and potential energy of masses, elastic potential energy of springs, dissipated energy of dampers, and elastic contact energy. Based on the law of conservation of energy, the energy of all the components above the track would be equal to the energy that is transferred into the track. The law of conservation of energy results in the following formulation:

$$\int \{m_1(\ddot{x}_1 + g) + m_2(\ddot{x}_2 + g)\}\dot{x}_2 \ + \Delta U_c = \Delta E$$

Where ΔE represents the total energy transferred into track and ΔU_c represents elastic energy of contact. Thus, the energy transferred into track can be estimated as:

$$\Delta E \cong \int \{m_1(\ddot{x}_1 + g) + m_2(\ddot{x}_2 + g)\}\dot{x}_2$$

The power transferred into the track is the product of the contact force and the vertical movement of the rail. The energy is obtained by integrating the power over a time span. In the TEM formulation, the contact force is estimated by acceleration calculations and masses ($m_1(\ddot{x}_1 + g) + m_2(\ddot{x}_2 + g)$), and the rail vertical velocity is estimated by the unsprung mass velocity ($\dot{x}_2$).

RESULTS

Simplified three DoF model and VAMPIRE® models were employed to assess the feasibility of the proposed TEM formulation at estimating the energy transferred into the track using eight different theoretical perturbations. Figure 3 compares the power calculated by VAMPIRE® simulation and the power estimated by TEM for a symmetrical long wavelength perturbation (wavelength: 8', amplitude: 0.5") in the top plot and asymmetrical short wavelength perturbation (wavelength: 4", amplitude: 0.008") in the bottom plot; the perturbations are implemented only on the right rail.

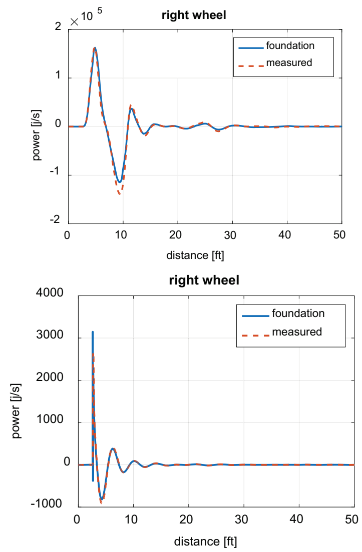

Figure 3. Example of Comparison between TEM and VAMPIRE® Derived Power

The results show that the worst-case cumulative estimation error between VAMPIRE® simulation and TEM formulation of a short wavelength perturbation is less than 15% for vertical force and less than 36% for energy. The worst-case cumulative estimation error is less than 11% for vertical force and less than 22% for energy on a long wavelength perturbation. However, the estimation errors are far less for the remaining six perturbations modeled in this study. Since the power (energy) estimation includes rail vertical velocity estimation errors, the results for estimated energy is expectedly less accurate than the estimate of forces. Therefore, it is possible the TEM force estimate might be more useful in practice than the TEM energy estimate.

CONCLUSIONS

A TEM formulation in vertical direction was developed using acceleration and mass from simple theoretical modeling. Wheel rail contact vertical forces estimated by the TEM formulation showed reasonable agreement with values calculated using VAMPIRE® while estimated energy resulted in larger error discrepancies. However, the results were limited to only the vertical direction and single perturbations.

FUTURE ACTION

The TEM formulation requires further evaluation with more comprehensive dynamic models, and with larger variety of track irregularities and their combinations. The results could be analyzed in frequency domain for multiple frequency bins for an attempt to associate each frequency bins' content to specific track damage (deterioration) modes. Moreover, further efforts are needed to generalize the TEM formulation to account for and assess its accuracy in lateral direction.

Finally, the formulation would have to be assessed experimentally by comparing TEM estimated forces with forces measured by Instrumented Wheel Sets (IWS), and by exploring the relationship between track degradation and TEM estimated forces and energy.

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KEYWORDS

Track, energy, damage, wheel rail forces, vehicle-track interaction, axle-box acceleration, VTI, track energy metric, TEM