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3D Dynamic Dry Friction Model for the Wheel-Rail Contact

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1. INTRODUCTION

Accurate estimation of the coefficient of friction (CoF) is very important for modeling railroad dynamics, reducing maintenance costs, and increasing safety in the long-term. The long term goal of this study is to quantify the correlation between the CoF determined from operational rail data and the CoF estimated using simulations based on newly developed 3D dry friction models for the wheel-rail interface. Currently, no other appropriate nonlinear CoF model exists for dry surfaces in the railroad system. Moreover, a 3-D nonlinear model has not been developed yet to include the relative lateral wheel motion which must be accounted for to correctly model railroad dynamics and the CoF since it changes the contact patch area. The main goal of this study is to introduce a newly developed 3D nonlinear dry CoF model, including the noted parameters, and to test the nonlinear CoF variation with dynamic parameters estimated from the simplified wheel-rail simulation model.

2. SIMULATION MODEL and CONDITION

The dynamic wheel-rail system is modeled as the mass-spring-damper system to simulate a generic locomotive having 4 axles of typical design. This system is modeled based on the assumptions below:

- The wheel tread is perfectly conical 1:20 (2.86°).
- The track is straight.
- Wheel clearance is 10*mm*.
- The track is rigidly fixed ground, i.e., there is no motion of the track.
- The wheel and the rail are made out of the typical rail steels.

The dynamic train model includes a main body, a wheelset, rails, and the track. All dynamic movements are obtained at the right wheel only. The model has three degrees of freedom (DoF): vertical and lateral displacements, and yaw rotation. The surface roughness is used as an excitation source. The method assumes that the wheel stays at a fixed point on the rail and rail roughness moves at a steady speed between the wheel and the rail. Hertzian theory is applied to calculate semi-elliptical wheel-rail contact patch dimensions, *a*: longitudinal direction and *b*: lateral direction. Hertz force law based on the concept of the Hertzian nonlinear contact spring is used to calculate the normal force at the contact between the wheel and the rail. The 3D dynamic CoF model is developed as Eq. 1. This model includes stick and slip components separately. To calculate this dynamic CoF variation, all necessary dynamic parameters are calculated, but they are not included in this paper due to the page limitation.

The simulation runs for 2.5 sec with 20m/s speed. The wheel is assumed to be initially stationary; then, a torque is applied to the wheel. The wheel speed reaches 20*m/s* as soon as it starts moving. The rail roughness is modeled as a sine wave with the maximum amplitude of rail roughness, 20μm. Only vertical rail roughness is modeled and the lateral variation is neglected. Initial conditions for the ODE of the model are arbitrarily selected.

Equation 1

$$\mu(t) = \underbrace{c_1\left(\frac{V^*(t)}{R^*(t)}\right)^{0.28}\frac{e^{-c_2\sqrt{V^*(t)}}}{1+c_3\left(\frac{a}{b}\right)^2 R^*(t)}}_{Slip\ Component} + \underbrace{\frac{c_4}{1+c_5\left(\frac{a}{b}\right)^2 R^*(t)}}_{Stick\ Component}$$

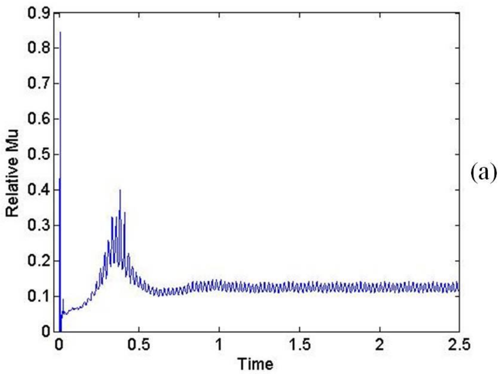
$$V^* = \frac{\pi V_{\tan}}{F_n}c_{\tan},\ T = \frac{-dh_o b}{\sigma_{\tan} a},\ R^* = 1-e^T,\ c_{\tan} = \sqrt{c_{long\_contact}^2 + c_{lat\_contact}^2},\ \sigma_{\tan} = \sqrt{\sigma_{long}^2+\sigma_{lat}^2}$$

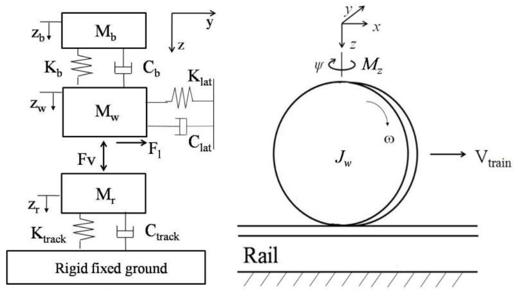
where V^* is a dimensionless velocity parameter. V^* includes the sliding velocity (V_s), the dynamic viscosity of the lubricant at the inlet conditions (η_i), a reference dynamic viscosity (η_o), the pressure viscosity coefficient (α). Terms c_1, c_2, c_3, c_4, and c_5 are empirical dimensionless constants fitted to the experimental data. They are c_1 = 2.31; c_2 = 7; c_3 = 0.322; c_4 = 12; $c_5 = 3.38\times10^4$. R^* is a dimensionless contact resistance. This R^* is related to the theoretical film (lubricant) thickness (h_o) for smooth surfaces, i.e., relative normal vibration. σ is the combined surface roughness and d = 0.0245 is an empirical constant fitted to the data.

3. RESULTS and CONLCUSIONS

The novelty of this CoF model is that it addresses the dry rail condition simultaneously including all major factors that impact the CoF variation in three dimensions. The newly developed CoF model shows the nonlinear variation of the total CoF, the stick component, and the slip component. In addition, it captures the maximum CoF value successfully. The CoF results do not show temporal similarity with evolution of any of the other dynamic parameters studied. Thus, we consider that the CoF has a highly nonlinear dependence on those parameters.

In conclusion, we believe that developing a good model, which helps understand the non-linear nature of wheel-rail friction is critical to the progress of railroad component technologies and rail safety. This study contributes to this effort by developing a unique 3-D nonlinear dry friction model that includes the dominant dynamic factors that influence the CoF variation. This model will be further expanded to include stochastic variations of the model parameters (such as rail roughness, contact patch area, lateral motion, sleeper distance, etc.) to yield still greater understanding of friction variance and effects for dry or lubricated rail.





(a) (b)

Figure 1. A mass-spring-damper model schematic for wheel-rail interaction with the body mass: (a) vertical vibration model and (b) wheel rotation model

Equations of Motion

Vertical Motion

$$a)\,Body: M_b\ddot{z}_b = -C_b\left(\dot{z}_b - \dot{z}_w\right) - K_b\left(z_b - z_w\right)$$

$$b)\,Wheel: M_w\ddot{z}_w = C_b\left(\dot{z}_b - \dot{z}_w\right) + K_b\left(z_b - z_w\right) - F_v$$

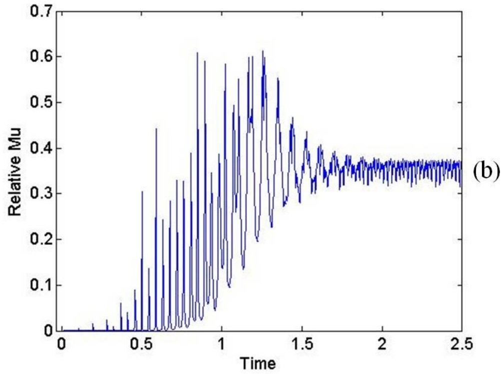
$$c)\,Rail: M_r\ddot{z}_r = F_v - C_{track}\left(\dot{z}_w - \dot{z}_r\right) - K_{track}\left(z_w - z_r\right)$$

Lateral Motion

$$M_w\ddot{y} = F_l - C_{lat}\dot{y} - K_{lat}y$$

Yaw Motion

$$J_w\ddot{\psi} = M_z - C_\theta\dot{\psi} - K_\theta\psi$$



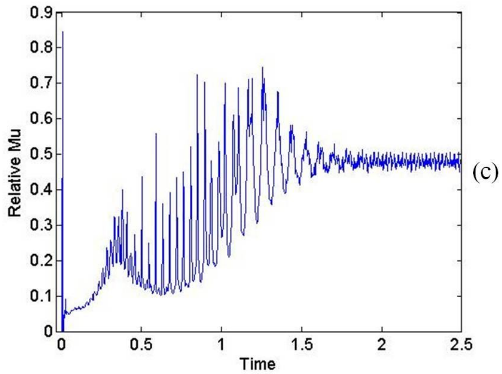


Figure 1. CoF results: (a) μ_{stick}, (b) μ_{slip}, and (c) μ_{total}

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This paper shortens the published paper, "Dynamic Model for the Wheel-Rail Contact Friction". For details, please read this paper.

REFERENCES

HW Lee, C. Sandu, and C. Holton, 2012, "Dynamic Model for the Wheel-Rail Contact Friction", Vehicle System Dynamics, 50, pp 299-321