

The Development of Terrain Pre-filtering Technique Based on Constraint Mode Tire Model

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ABSTRACT

The vertical force generated from terrain-tire interaction has long been of interest for vehicle dynamic simulations and chassis development. To improve simulation efficiency while still providing reliable load prediction, a terrain pre-filtering technique using a constraint mode tire model is developed. The wheel is assumed to convey one quarter of the vehicle load constantly. At each location along the tire's path, the wheel center height is adjusted until the spindle load reaches the pre-designated load. The resultant vertical trajectory of the wheel center can be used as an equivalent terrain profile input to a simplified tire model. During iterative simulations, the filtered terrain profile, coupled with a simple point follower tire model is used to predict the spindle force. The same vehicle dynamic simulation system coupled with constraint mode tire model is built to generate reference forces. This terrain pre-filtering technique proves to improve the computational efficiency by three orders of magnitude with no statistically significant change in resultant load prediction.

CITATION: Ma, R., Chin, P., Ferris, J., Cheng, C. et al., "The Development of Terrain Pre-filtering Technique Based on Constraint Mode Tire Model," *SAE Int. J. Passeng. Cars - Mech. Syst.* 8(3):2015, doi:10.4271/2015-01-9113.

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1. INTRODUCTION

Knowledge of vehicle chassis loads is critical for chassis designers since these loads act as the component excitation essential to fatigue analysis. However, actual loads are only available at the conclusion of the design and development process when it is difficult and expensive to make design modifications. One difficulty lies in the fact that the chassis loads are the response of the system to the main excitation to the chassis: the terrain. In this way the chassis loads change as the suspension design changes. To mitigate this problem, a

well-established load prediction process based on a constant terrain excitation, not a constant set of chassis loads, is advantageous. Although deformable terrain can be a significant excitation to off-road vehicles, this work focuses on non-deformable terrain and the excitation to on-road vehicles. Non-deformable terrain imposes unilateral geometric boundary constraints on rolling tires to which the chassis responds by generating loads. Thus a vehicle dynamic model, a tire model, and high fidelity terrain measurements are required to provide representative chassis loads for fatigue estimation and reliability analysis.

The vehicle and tire models should accurately emulate the behavior of a real vehicle and provide reliable vehicle responses to terrain excitations. Commercial multi-body dynamic software packages produce accurate chassis loads, but the use of these models is too computationally expensive for the iterative design process due to the large data size of the terrain profile and the complexity of the tire model. A simplified tire model that is far more computationally efficient, yet provides nearly identical simulation results, is required when exploring numerous design options. The simplest and most

computationally efficient form of a tire model is the ubiquitous point-follower model (a simple spring). Due to its simplicity, the bridging and enveloping properties of the tire are neglected and the accuracy of the predicted force is poor. As an improvement to the above point-follower approach, it is presently shown that an equivalent terrain profile, for use with a simplified tire model, can be generated to maintain the computational efficiency advantage of the simplified tire model and provide reliable preliminary chassis load estimation.

The objective of this work is to develop a terrain pre-filtering technique that results in an equivalent terrain profile that provides reliable estimates of chassis loads when the vehicle dynamics are simulated with a computationally efficient point-follower tire model. Since the focus of this work is the tire model, not a specific vehicle model, a simple seven-degree-of-freedom (7-DOF) vehicle model is used throughout. This work proceeds as follows. First, 7-DOF vehicle models and the constraint mode tire model are reviewed. Next, the terrain pre-filtering technique based on constraint mode tire model is developed. The concept is demonstrated through an example in which the Proposed Method is compared to two reference methods: The Reference-Best method is developed to appraise the accuracy of the Proposed Method and the Reference-Fastest method is developed to appraise the computational speed. Specifically, the Reference-Best method produces the reference load case using the full constraint mode tire model with the original terrain profile as input. The spindle loads predicted by the Proposed Method are simulated and compared with the reference load to demonstrate the accuracy of the proposed terrain pre-filtering technique. The Reference-Fastest method produces a load case using a point-follower tire model with the original terrain profile as input and the resulting computational efficiency is compared to the efficiency of the Proposed Method. These preliminary results are very promising for efficiently predicting accurate chassis loads for making early design decisions.

2. BACKGROUND

2.1. Vehicle Dynamic Simulation Model

An accurate and computationally efficient vehicle dynamic simulation model is essential for chassis load prediction. Chul and Ro have shown that a simple seven-degree-of-freedom (7-DOF) vehicle model is able to accurately portray vehicle ride dynamics [1]. The vertical motions of the four suspensions are considered to be lumped unsprung masses. Similarly, the bounce, pitch, and roll of the vehicle body is considered a lumped sprung mass. A 7-DOF model for vehicle ride dynamics is shown in Figure 1, with the equation of motion included in the original reference. The model is excited by the terrain profile input and only applies to low speed application in this paper. Therefore the aerodynamic loads can be neglected.

Müller developed a system identification process to accurately estimate 7-DOF vehicle system parameters [2]. The vehicle is excited by a speed bump and an optimization method is applied to estimate the model parameters through the vehicle response comparison. A simple point follower tire model is used in the calibration process and can be substituted later by more detailed models to address the tire bridging and enveloping properties and provide more accurate

spindle load estimation. As the complexity of the tire model increases, the computational efficiency decreases and the simulation process becomes more time consuming.

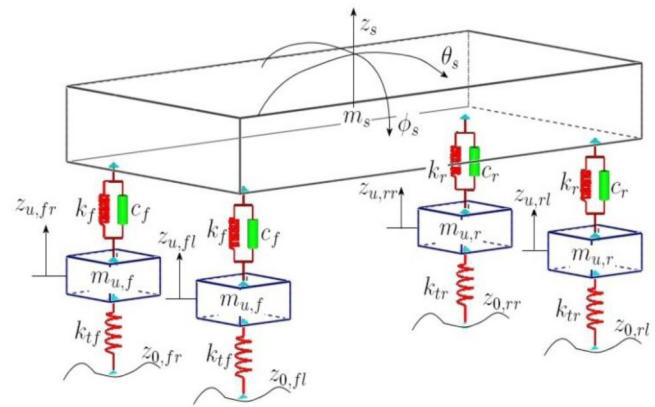


Figure 1. 7 DOF Vehicle Model [1]

2.2. Constraint Mode Tire Model

In this work, a constraint mode tire model is used as a filter to generate the equivalent terrain profile input. The constraint-mode tire model is used with the 7-DOF vehicle model to produce the Reference-Best load signals. The constraint-mode model comprises a segmented elastic ring linked to the wheel center by a series of springs as shown in Figure 2 [3].

Each segment is modeled as an Euler Beam and Hamilton's Principle is used to form the quasi-static equations. The tire deformation is quantified by the radial displacement of each segment, $\{\mathbf{u}\}$. The tire deformation is assumed to be adequately represented by equation (1).

$$[\mathbf{K}]\{\mathbf{u}\} = \{\mathbf{F}\}$$

(1)

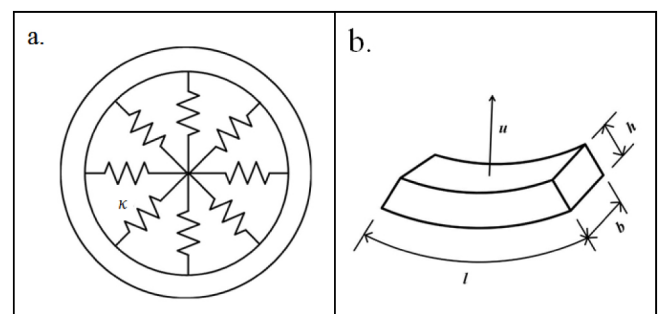


Figure 2. Constraint Mode Tire Model Scheme

The physical degrees of freedom comprise active and omitted degrees of freedom, represented by 'a' and 'o' respectively. In this formulation, the active degrees of freedom are those in contact with the terrain, all others are omitted degrees of freedom. The radial displacement $\{\mathbf{u}\}$ is reordered according to the orthonormal sorting matrix $[\mathbf{S}]$, as shown in equation (2). This sorting matrix is populated by zeros, except for a single entry of 'one' for each row and each column. The stiffness matrix $[\mathbf{K}]$ and force vector $\{\mathbf{F}\}$ are reordered and partitioned as given in equation (3).



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$$\{\mathbf{u}\} = \begin{bmatrix} [\mathbf{S}^a] & [\mathbf{S}^o] \end{bmatrix} \begin{Bmatrix} \{\hat{\mathbf{u}}^a\} \\ \{\hat{\mathbf{u}}^o\} \end{Bmatrix} = [\mathbf{S}] \{\hat{\mathbf{u}}\} \quad (2)$$

$$[\hat{\mathbf{K}}] = [\mathbf{S}]^T [\mathbf{K}] [\mathbf{S}], \quad \{\hat{\mathbf{F}}\} = [\mathbf{S}]^T \{\mathbf{F}\} \quad (3)$$

Next the sorted matrix and vectors are substituted into [equation \(1\)](#), yielding [equation \(4\)](#). From the lower set of equations given in [equation \(4\)](#), the omitted degrees of freedom are known from the active degrees of freedom according, given in [equation \(5\)](#). The entire deformed shape of the tire, given the deformations at the active constraints is given in [equation \(6\)](#) according to Guyan reduction [5]. The radial forces are calculated from [equation \(1\)](#).

$$[\hat{\mathbf{K}}] \{\hat{\mathbf{u}}\} = \begin{bmatrix} [\hat{\mathbf{K}}^{aa}] & [\hat{\mathbf{K}}^{ao}] \\ [\hat{\mathbf{K}}^{oa}] & [\hat{\mathbf{K}}^{oo}] \end{bmatrix} \begin{Bmatrix} \{\hat{\mathbf{u}}^a\} \\ \{\hat{\mathbf{u}}^o\} \end{Bmatrix} = \begin{Bmatrix} \{\hat{\mathbf{F}}^a\} \\ \{\mathbf{0}\} \end{Bmatrix} = \{\hat{\mathbf{F}}\} \quad (4)$$

$$\{\hat{\mathbf{u}}^o\} = -[\hat{\mathbf{K}}^{oo}]^{-1} [\hat{\mathbf{K}}^{oa}] \{\hat{\mathbf{u}}^a\} \quad (5)$$

$$\{\mathbf{u}\} = [\mathbf{S}] \begin{Bmatrix} \{\hat{\mathbf{u}}^a\} \\ \{\hat{\mathbf{u}}^o\} \end{Bmatrix} = [\mathbf{S}] \begin{bmatrix} [\mathbf{I}] \\ -[\hat{\mathbf{K}}^{oo}]^{-1} [\hat{\mathbf{K}}^{oa}] \end{bmatrix} \{\hat{\mathbf{u}}^a\} \quad (6)$$

Given a spindle position above a given terrain surface, the deformed shape of the tire is calculated recursively by incrementally adding active degrees of freedom and solving for the resulting tire displacements, $\{\mathbf{u}\}$, to affect the unidirectional constraint on the tire surface (that is, the terrain must be underneath the tire at any contact area) [3]. The first trial constraint mode is the circular undeformed shape of the tire, located at a prescribed vertical position above the terrain surface. The recursive process continues through steps (a) through (e), shown below [6].

- Identify the set of degrees of freedom where the road surface impinges on the current trial constraint mode.
- Sort the degrees of freedom with respect to the magnitude of impingement.
- End the iteration process if no significant impingement exists.
- Augment the current set of active degrees of freedom with the degree of freedom that has the greatest impingement (and those that impinge within some very small tolerance of that greatest impingement, if applicable).
- Develop a new trial constraint mode based on this augmented set of active constraints.

So, given a spindle position above the given terrain surface, the resulting active constraints are identified using this recursive process. At each iteration in the process, a new orthonormal sorting matrix, $[\mathbf{S}]$, is created resulting in a new tire shape, calculated by [equation \(6\)](#), and a set of radial tire forces, calculated by [equation \(1\)](#). Given the simple circular geometry of the problem, the resulting vertical spindle force is easily calculated from these radial forces.

Next, consider the opposite scheme in which the spindle load is given and the corresponding spindle position must be determined. The issue is to determine the proper wheel center height so that this designated spindle load is achieved for that given terrain surface. Clearly the vertical spindle load will be monotonically, though perhaps not smoothly, increasing as the wheel center height decreases (as the tire becomes more compressed). A simple zero-crossing search (the Illinois algorithm, for example) will determine the height at which this pre-designated load is achieved. This is the basis for developing the terrain pre-filtering technique.

2.3. Equivalent Terrain Profile

To improve vehicle dynamic simulation efficiency, a considerable amount of research has been done to generate an effective road profile for a simpler planar tire model. Pacejka introduced the two-point follower technique as shown in [Figure 3](#) [7]. The basic curve is shown as a dotted line and is defined to represent the decomposition of vertical force change to a short rectangular obstacle [8]. Note that the basic curve is a notional function of the force, not a geometric description of the terrain. A follower is defined as a line segment of a constant length, the shift length (l_s), is used to form the effective road height from the basic curve (from a function of the vertical force). Specifically, as the endpoints of the follower trace the basic curve, the midpoint height defines the equivalent height, shown in [Figure 3](#) as a solid curved line. The inclination angle of the follower corresponds to the slope of the effective road profile. This connection between the vertical loading and the effective road profile is used in the development of the proposed terrain pre-filtering method.

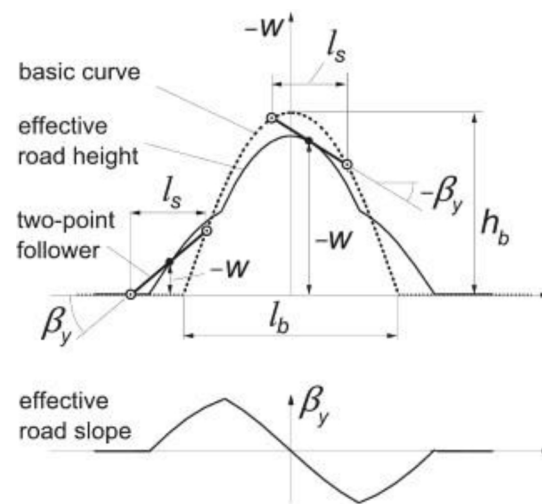


Figure 3. Two point follower method to determine the effective road profile

Schmeitz applied two elliptical cams connected by the follower at a distance equal to the shift length l_s to obtain the effective road height as shown in [Figure 4](#) [9]. The change in height of the follower's midpoint and its inclination represent the effective height and effective slope respectively. The geometric smoothing is a main feature of the proposed pre-filtering technique.