A NOVEL COMPARATIVE APPROACH TO EVALUATE VEHICLE ROLLOVER PROPENSITY

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Abstract

This paper proposes a novel comparative metric to evaluate vehicle rollover propensity based on a frequency-domain representation of the Zero Moment Point (ZMP). Unlike other rollover metrics such as the Static Stability factor which is based on steady-state behavior, or the Load Transfer Ratio which requires calculation of tire forces, the ZMP is based on a simplified kinematic model of the vehicle and analysis of the contact point of the vehicle relative to the edge of the support polygon. Previous work validated the ZMP experimentally in its ability to predict wheel lift in the time domain. This work explores the use of the ZMP in the frequency domain to specifically highlight the rollover mode of the vehicle, to allow a chassis designer to focus on design changes to improve rollover propensity.

1. INTRODUCTION

This paper proposes a novel comparative approach to evaluate vehicle rollover propensity. At present, there is no standard protocol to qualitatively examine the risk of vehicle rollover during a vehicle design process. Vehicle design engineers have some simple design tools to determine rollover metrics including the Static Stability Factor (SSF) [1] or experimental tests such as side-pull test [1], tilt-table test [1], centrifugal test [1], etc. However, there are a number of inherent disadvantages that come along with these metrics and these tests. As commonly known, the SSF is derived based on a steady-state turn, so it ignores the dynamic effects of the vehicle. Furthermore, according to NHTSA [1], it is possible to artificially improve the outcomes of the previously mentioned experimental tests with suspension alterations. Because of the importance of predicting rollover onset or behavior, there have been substantial efforts dedicated to study vehicle rollover and a considerable number of rollover metrics have been proposed [2, 3, 4, 5, 6, 7, 8]. Nevertheless, these previous works have metrics primarily focused on rollover detection rather than using them as a design tool that can quantify vehicle rollover propensity.

As shown in [9, 10], rollover mechanisms are not solely dependent on any particular state, but rather are the result of a complex interplay between several different vehicle states. Moreover, in the same work, it has been shown that a technique called the Zero-Moment Point (ZMP) method [11] is a valid indicator to precisely predict the onset of vehicle rollover. The ZMP method allows the dynamic effects to be included in the rollover prediction algorithm. This paper investigates a frequency-domain representation of the ZMP that utilizes a vehicle dynamic model and the frequency response to qualitatively evaluate vehicle rollover propensity. The benefit of this metric versus a similar approach such as the Load Transfer Ratio (LTR) [2] is that it does not artificially saturate and is clearly based on the contact polygon of the vehicle. Although this proposed approach cannot analytically determine whether or not the vehicle will roll over, it gives an engineer a benchmark, namely rollover margin, to see whether a design is improved or worsened from rollover perspective, compared to the baseline design. This approach also highlights the rollover mode of the vehicle which allows the engineer to understand what the particular frequency that dominates the rollover mode of the vehicle is, so he/she can modify the configuration of the vehicle suspension accordingly to reduce the likelihood of vehicle rollover. Additionally, this approach can be considered as one of the optimization criteria apart from ride quality in a suspension design process.

The remainder of the paper is organized as follows: Section 2 outlines the procedure used to infer rollover propensity. Section 3 introduces in detail the concept of the zero-moment point, which is a main technique used to determine vehicle rollover propensity. The results that show the effectiveness of this approach are given in Section 4. Conclusions then summarize the main points of this paper.

2. PROCEDURE

To measure vehicle rollover propensity, a technique called the Zero-Moment Point (ZMP) [11] is applied. By definition, the ZMP is the point on the ground where the summation of the tipping moments acting on an object, due to gravity and inertia forces, equals zero [12]. Typically, the ZMP has been used to determine stability of a kinematic chain, especially that of biped robots [13]. For the chain to be dynamically stable, the location of the ZMP must lie within the support polygon. Nevertheless, if the support polygon is not large enough to encompass the location of the ZMP to balance the action of external moments, this can result in overturn of the kinematic chain [14].

The key insight of this paper and prior work examining the ZMP, is that the proximity of the ZMP to the edge of the support polygon of a vehicle can be used to evaluate rollover propensity of a vehicle. Further, this proximity can be inferred by the ZMP's distance relative to the vehicle centerline, hereafter called y_{zmp}. The derivation of the lateral location of the ZMP will be given in Section 3. In this work, the lateral location of ZMP is represented in frequency domain to qualitatively evaluate vehicle rollover propensity. A process of rollover propensity evaluation is summarized in Figure 1.

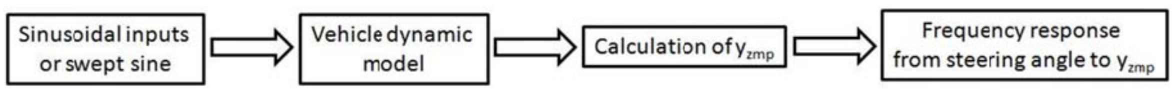


Figure 1Process of rollover propensity evaluation

To obtain a frequency response, a series of sinusoidal inputs or swept sine is fed to an experimental vehicle or a vehicle dynamic model. The vehicle dynamic model used here can be any models that can output necessary states to the calculation of the lateral location of the ZMP, discussed below. From these states, the lateral location of the ZMP is computed. Then, the frequency response from the steering input to the lateral location of the ZMP is constructed by using correlation frequency response analysis [15] for the case of the sinusoidal inputs, or using Short-Time Fourier Transform (STFT) for the case of the swept sine. Analysis of the magnitude of the frequency response then highlights the frequencies of concern for rollover.

3. ZERO-MOMENT POINT AND ITS APPLICATION AS ROLLOVER THREAT INDEX

The concept of zero-moment point (ZMP) was first formally developed and introduced by Vukobratovic in 1968 [11]. This concept has been very useful and is now widely used in bipedal robotics research. Biped robotics scientists have applied the concept to preserve robots' dynamic balance during walking, or, in other words, to maintain stability of the robots, preventing the robots from overturning. Today, there are hundreds of biped walking robots implemented with this algorithm, for instance, Honda's humanoid robots [13]. Moreover, many researchers used the ZMP as a stability constraint for mobile manipulators to prevent the overturn of the mobile manipulators due to their own dynamics [16, 17].

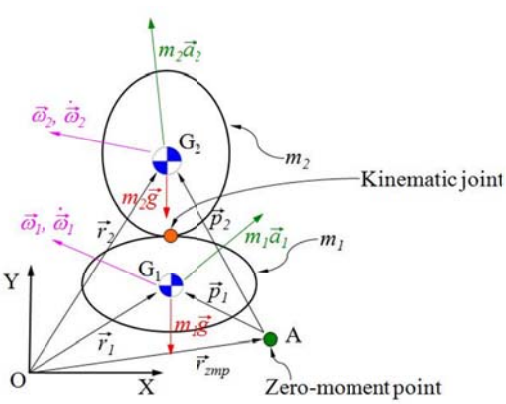


Figure 2 Free-body diagram of two-link kinematic chain

As mentioned in Section 2, the ZMP is the point on the ground where the summation of the tipping moments acting on an object, due to gravity and inertia forces, equals zero [12]. The location of the ZMP must lie within the supporting polygon to maintain the dynamic stability of a kinematic chain; otherwise, the chain will turn over. To find the location of the ZMP, the free-body diagram of a two-link kinematic in Figure 2 is considered. By using general equations of motion [18] and D'Alembert's principle [19], the moment equation about point A in Figure 2 induced by inertial forces and gravity is:

$$\vec{M}_A = \vec{p}_1 \times m_1\vec{a}_{G_1} + \mathbf{I}_1\dot{\vec{\omega}}_1 + \vec{\omega}_1 \times \mathbf{I}_1\vec{\omega}_1 - \vec{p}_1 \times m_1\vec{g} + \vec{p}_2 \times m_2\vec{a}_{G_2} + \mathbf{I}_2\dot{\vec{\omega}}_2 + \vec{\omega}_2 \times \mathbf{I}_2\vec{\omega}_2 - \vec{p}_2 \times m_2\vec{g} \quad (1)$$

where m_i is the mass of the i[th] body, $\mathbf{I}_i$ is the inertia tensor of the i[th] body, $\vec{a}_i$ is the linear acceleration of the i[th] body, $\vec{\omega}_i$ is the angular velocity of the i[th] body, $\vec{p}_i = \vec{r}_i - \vec{r}_{zmp}$, $\vec{r}_i$ is the position vector of the center of gravity (CG) of the i[th] body, $\vec{r}_{zmp}$ is the position vector of the ZMP, and $\vec{g}$ is the gravitational acceleration. If $\vec{M}_A = [0\ 0\ M_{Az}]^T$, the point A becomes a zero-moment point.

Table 1 Nomenclature for rigid vehicle model

Symbol	m	a	b	h	T	$I_{xx, yy, zz}$	$I_{xz, yz}$
Definition	Vehicle mass	Distance from CG to front axle	Distance from CG to rear axle	Height of CG	Track width	Mass moment of inertia	Product mass moment of inertia
Symbol	φ_r	φ_t	θ	p	q	r	a_G
Definition	Roll angle	Roll angle of banked surface	Pitch angle	Roll rate	Pitch rate	Yaw rate	CG's acceleration[a]

[a]Subscripts x, y, and z indicate accelerations in x-, y-, and z- directions, respectively.

To apply the concept of the ZMP to a vehicle system, a vehicle is modeled as a rigid body shown in Figure 3. In the figure, the coordinates oxyz are fixed with the vehicle at the center of gravity of the vehicle (point G). Point Q is a zero-moment point located by $\vec{r}_{zmp}$ and is always physically on the ground. To calculate the location of the zero-moment point, we assume that the vehicle is symmetrical in the xz-plane ($I_{xy} = 0$), and the vehicle is free to move in any directions. The nomenclature used in this section is defined in Table 1, Figure 3, and Figure 4. Considering Figure 4, the location of the ZMP may be expressed as:

$$\vec{r}_{zmp} = x_{zmp}\vec{i} + y_{zmp}\vec{j} + \left[h + \frac{T}{2}\left|\tan(\phi_r - \phi_t)\right| - y_{zmp}\tan(\phi_r - \phi_t)\right]\vec{k} \quad (2)$$

By using Eq. 1, the lateral location of the ZMP can be expressed as:

$$\begin{aligned} y_{zmp} = \{&mT\left|\tan(\phi_r - \phi_t)\right|\left[g\cos(\theta)\sin(\phi_r) - a_{Gy}\right] + 2\left[-I_{xx}\dot{p} + I_{xz}pq + I_{yz}q^2 + (I_{yy} - I_{zz})qr - I_{yz}r^2\right. \\ &\left. + I_{xz}\dot{r} + mgh\cos(\theta)\sin(\phi_r) - mha_{Gy}\right\} / \left\{2m\left[g\cos(\theta)\cos(\phi_t)\sec(\phi_r - \phi_t) - a_{Gz} - a_{Gy}\tan(\phi_r - \phi_t)\right]\right\} \end{aligned} \quad (3)$$

Since the main focus of this work is to determine vehicle rollover propensity, only the expression of y_{zmp} is presented for brevity. The complete solutions of the location of the ZMP can be found in [9, 20]. Additionally, the fidelity of the above equation to predict vehicle rollover was confirmed in [9, 10, 20].

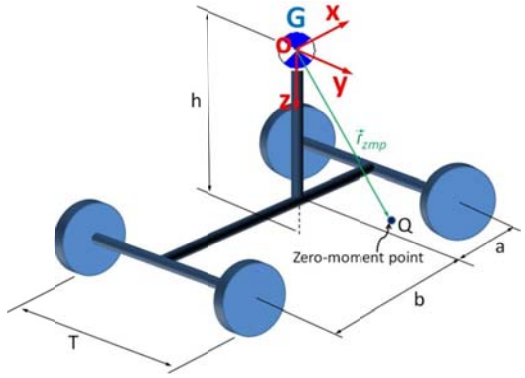
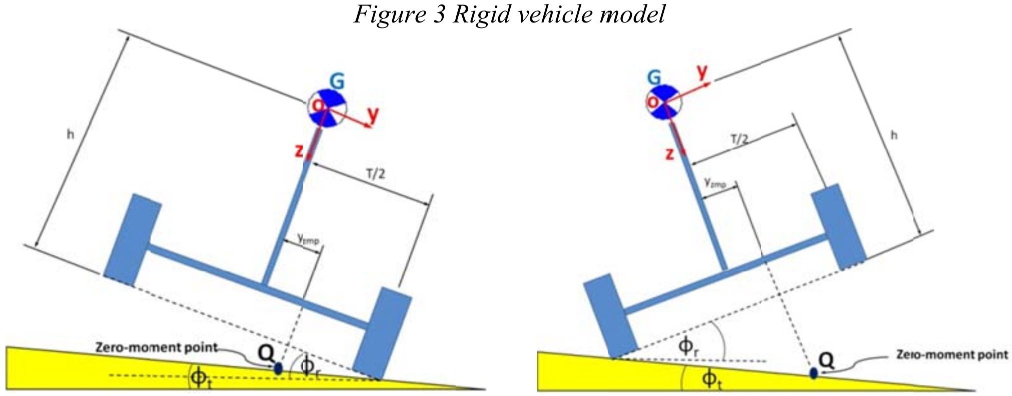


Figure 3 Rigid vehicle model



(a) (b)

Figure 4 Rigid vehicle model on banked surface (a) $\phi_r \geq \phi_t$ (b) $\phi_r < \phi_t$

4. RESULTS

To prove the concept of this approach, a vehicle model is needed to represent a real vehicle. In this work, a low-order, yaw-roll vehicle dynamic model [20] was selected and implemented in simulations. However, it is worth noting the vehicle dynamic model that will be used in this approach can be any model or instrumented vehicle that generates the necessary states for the calculation of y_{zmp}. The accuracy of this yaw-roll vehicle model is shown in [20].

To show the effectiveness of this approach, to parameter sets were considered. The first set is the parameters of an unladen 1989 GMC 2500 pick-up truck. The other is those of the same truck with the additional weight of 784 kg added to the rack over the truck's bed to make it more rollover-prone. The parameters of both trucks are available in [20] and based off of experimental measurements therein from this same vehicle. A series of sinusoidal road-wheel steering inputs whose frequency ranges from 0.1 Hz to 3.0 Hz were given to the model, and the truck's states were then recorded and later used to compute the corresponding y_{zmp}. The frequency responses from the steering input to the y_{zmp} were constructed by using the correlation frequency response analysis as described in [15].

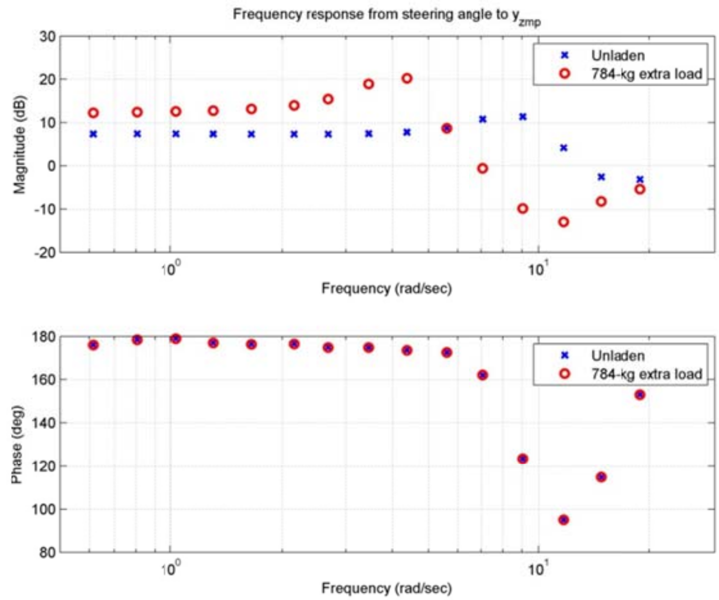


Figure 5 Frequency responses of the unladen and loaded trucks from road-wheel steering angle to y_{zmp}

Figure 5 shows the frequency responses from the steering input to the lateral location of the ZMP. From the figure, it is clear that the truck with the extra weight has higher rollover propensity than the unladen truck, and that the roll mode of this vehicle has shifted to a lower frequency region than the unloaded vehicle. Additionally, the gain from steering input to possible wheel lift exhibits a 10-dB increase. The shift in frequency agrees with intuition since the loaded truck has much more inertia, thus making it substantially slower to respond to the high-frequency inputs. An interesting observation is that the phase of the ZMP response is not affected by vehicle loading, and thus control methods that primarily utilize phase distortions to improve rollover behavior might be particularly effective. This illustration of the change in the rollover modes in both frequency and amplitude with increased loading of the vehicle are difficult or impossible to obtain with other rollover metrics.

5. CONCLUSIONS

A novel comparative approach to evaluate vehicle rollover propensity has been proposed in this paper. The approach utilizes the concepts of zero-moment point and frequency response as tools to determine rollover margin of a vehicle. Using a simulated vehicle model, the effectiveness of the approach was examined across a changing load condition, revealing that the gain between steering input and stability margin changes as expected, but the phase is static with respect to vehicle loading. The results indicate that this approach can be used as one of the design tools to help an engineer understand the dynamic effects from a rollover perspective and design a vehicle that has more "rollover resistance".

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