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EFFECTS OF GENERAL ASYMMETRIES ON THE ROAD VEHICLE LATERAL VIBRATION

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Abstract

The mechanistic deterioration of pavements pose an eccentric kinematic excitation to the vehicle wheels, a situation that amplifies the lateral vibration of the vehicles. Additionally, asymmetric loading of these vehicles translating over the pavement potholes could shift the centre of mass away from the centre of geometry in the lateral direction. Most revised literatures seem to have not investigated the effects of general asymmetries on the lateral vibration separately. This study modelled the effects of combined general asymmetries on the lateral vibration of full car sprung mass. About 27 general symmetrical (control model) and asymmetrical 3D 18 DOF models were developed using SIMWISE 4D and investigated. Depending on the type of loading configuration, it was found that the lateral dynamic response of the sprung mass is seemingly defined by the nature of the kinematic excitation. The developed study models could be used in analysis of vehicle accident and the study findings could contribute to an understanding of full vehicle vibrations.

Key Words - lateral vibration, asymmetric loading, eccentric kinematic excitation, road vehicle

1. Introduction

Understanding the complete and detailed vibration of a vehicle is crucial to identifying factors that may cause harm to passengers, drivers, vehicles, or pavements [1]. However, most studies on vehicle vibrations do not investigate the effects of general asymmetries, such as asymmetric loading configurations and eccentric wheel kinematic excitations, on the lateral dynamic response of the vehicle. The combined effects of these asymmetries for a given vehicle payload could lead to harmful dynamic responses in the lateral direction. The wheel-pavement interaction effects resulting from pavement distress, such as potholes, may be eccentric and could also affect the lateral dynamic response of the vehicle's sprung mass. The type of axle configuration used on the vehicle can also influence these effects.

Furthermore, the nature of loading configurations used could shift the center of mass away from the center of geometry, introducing rotational dynamic responses that could interfere destructively with the vehicle's lateral vibrations and amplify the lateral dynamic response of the sprung mass.

This study focuses solely on investigating the effects of general asymmetries on the lateral vibration of the vehicle's sprung mass while traveling at 60km/h over a pothole with a depth of 25mm. However, it contributes to the findings of several other studies on full vehicle dynamic responses. Previous studies (such as in [2]) have only focused on either the vertical dynamic responses of the vehicle influenced by combined general asymmetries or the lateral vibration of the vehicle during cornering, without considering the effects of combined general asymmetries.

This study will use a 3D 18 DOF full car model with dependent axle configurations in SIMWISE 4D to investigate these effects on the lateral vibration of the vehicle. The study is structured as follows: a literature review will be presented first, followed by the methodology used to study the effects of general asymmetries on the lateral vibration of the vehicle. The simulation results and their discussion will be presented next, followed by the conclusions and recommendations for future research.

2. Revised Literature

Over the past decades, most literatures have investigated on vehicle vibration, having illustrated several approaches used in numerically modelling the vehicle vibration using the mass spring damper systems. These models evolve around the Multi-body multiple Degree of Freedom (MDOF) models range from quarter car models (used in [3], [4]) to full car models demonstrated in many literatures including that of [5], [6], [7] and [8]. Most of the literatures revised have only investigated the effects of individual asymmetries on the vertical vibration of vehicles but the lateral vibration.

In an effort to understand the effects of lateral vibration, most literatures presented study models ranging from independent vehicle models to wind-vehicle-track interactive models to understand the interactive dynamic response of the track or the vehicle due to cross winds.

Several researchers including [9] and [10] had proposed vehicle-track interactive models. Most of these vehicles could be coupled by interaction matrices and load vectors using unsteady cross wind (defined by weighing functions) as kinematic excitations to the system.

Literatures such as [11] and [1] has also investigated the effects of cornering in an attempt to understand the lateral vibration of the vehicle. Most of these studies on assessing the lateral dynamic response of vehicles did not account for the nature of the track irregularities or the mechanism to which the wheels interact with these irregularities or the influence of asymmetric loading to the lateral displacements of the vehicle under study.

Lateral dynamic response of the vehicles could be the contributing factor to occurrence of accidents [1], most likely when vehicles being driven over defective road pavements or rails. Same as when the train move through different terrains with varying ground roughness and turbulent intensity [12], the road vehicles wheel could be interacting with varying pavement potholes of varying kinematic excitation configurations. The responses of the suspension system to these defects could alter the sprung mass dynamic responses relatively, whose lateral dynamic response could be amplified. This is critical in analyzing the influence of wheels eccentric kinematic excitation and the asymmetric loading when decomposing the vehicle dynamic response hence understanding vehicle dynamic due occurrences such as accidents or unexplained components damaging events. The couple vehicle-track systems dynamic performance are affected by the various kinematic excitations modes such as average cross winds, fluctuating cross winds and track irregularities [9].

Utilization of computer-based simulations software's had enabled establishments of easier methods of conducting vibration studies on vehicle-pavement or train-rail interactive studies. Vehicle dynamic simulation package such as VAMPIRE (used in [13] to assess train derailments influenced by cross winds) and ADAMS has the capability to be applied in vehicle vibration studies, allowing the vehicle suspensions components and wheel interactions detailed modelling. SIMWISE 4D is also one of these software's that can allow vibration studies on various vehicle-pavement interactions, hence being used in this study.

3. Methodology

An 18 DOF full car model was developed using SIMWISE 4D as indicated in Fig 1 and 2. The geometry of these model were used to define other models used herein.

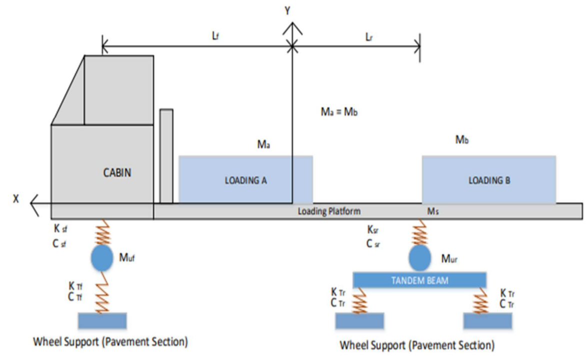

Figure 1 : 18 DOF Vehicle Model with dependent axles [Side View]

The model comprises of both the front and rear dependent axles, which are connected to the sprung mass through linear spring models that represent conventional leaf springs as defined in [14]. Fig 1 shows that two payloads with different masses, Ma and Mb, are placed on the loading platform of the vehicle using different loading configurations.

To ensure system stability, lateral linear springs were introduced with stiffness strengths and damping coefficients similar to those used for the leaf springs. This was done to define the lateral structural support provided by the conventional leaf springs. The wheel-pavement model is defined by a single point pavement contact linear spring model directly linked to the front axles, while for the rear tandem drive suspension system, it is linked to the tandem beams using a walking beams model commonly used in literature, such as [15]. They are as indicated in Fig 2.

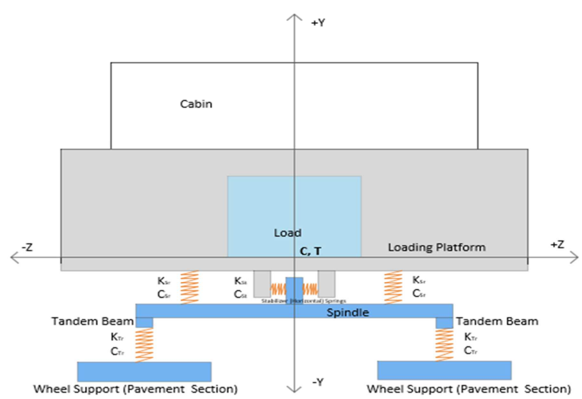

Figure 2: 18 DOF Vehicle Model with dependent axles [Back View]

Additionally, the kinematic excitation is applied to the pavement sections shown in Fig 1 and 2 using mathematical functions described in this section.

The suspension and wheel stiffness and damping coefficients are defined using parameters from [16], which are listed in Table 1.

Table 1
Study Vehicle Models Suspension Parameters [16]

Parameters Description	Parameter
Mass of the Truck (m_s)	7200.0 kg
Truck Pitch moment of inertia (I)	100000.0 kgm^2
Front tire and axle assembly mass (m_{uf})	353.0 kg
Rear tire and axle assembly mass (m_{ur})	653.0 kg
Front axle suspension stiffness (K_{sf})	295.3 kN/m
Rear axle suspension stiffness (K_{sr})	797.3 kN/m
Front axle suspension damping coefficient (C_{sf})	2.9 kNs/m
Rear axle suspension damping coefficient (C_{sr})	5.9 kNs/m
Front tire suspension stiffness (K_{Tf})	1100.0 kN/m
Rear tire suspension stiffness (K_{Tr})	2200.0 kN/m
Front tire suspension damping coefficient (C_{Tf})	0.4 kNs/m
Rear tire suspension damping coefficient (C_{Tr})	0.8 kNs/m
Distance from front axle to Center of Gravity (C)	3.757 m
Distance from rear axle to Center of Gravity(C)	2.441 m

This study defines a vehicle as being symmetrically loaded (Loading A) when all of the payloads have longitudinal central axes that are parallel or collinear with the vehicle loading bed's central longitudinal axis (Z-axis). Symmetrical wheel kinematic excitations (kinematic excitation I) are defined as the interaction of all vehicle wheels at the same time with pavement distress factors, specifically potholes of 25mm depth. Several models were developed with different loading configurations and kinematic excitations, as shown in Table 2.

Table 2
Study Models Kinematic Excitation and Asymmetric Loading Configurations Definitions [17]

Excitation Configuration \ Loading Configuration		A	B	C	D	E
I		AI	B I	C I	D I	E I
II		AII	B II	C II	D II	E II
III		AIII	B III	C III	D III	E III
IV		AIV	B IV	C IV	D IV	E IV
V		AV	B V	C V	D V	E V

Other loading configurations that are asymmetric may result in dynamic responses similar to those of Loading B (all payloads loaded along the longest edge of the payload with their longitudinal axes parallel to that of the loading platform) and Loading E (all payloads loaded towards the back corner of the loading platform). Similarly, other combined eccentric kinematic excitations may cause dynamic responses similar to those of Kinematic Excitation III (all back wheels are kinematically excited at the same time) and Kinematic Excitation V (only the front left and the back front left wheels are kinematically excited by the pavement distress factors at the same time).

The interaction between potholes and vehicle wheels is often eccentric because potholes are usually localized. Therefore, this study used numerically defined pothole depths of 25 mm. In addition, the dynamic response of a vehicle to kinematic excitation varies depending on its speed, so a vehicle speed of 60 km/h was chosen. The rated ratio of speed to displacement was used to determine the appropriate angular velocity for the sine wave input function used in the study models. The input excitation function was conditioned using a time-bound statement such that the first half trough of the sine function response during the study period of interest (10 seconds < time < 25 seconds) would define the first condition of the input excitation, while the displacement was zero before and after that time. The function is shown below.

*If(and(time>11.3 s, time<12.1 s), (25*Sin(2.4*time)), 0)*

The simulations of different models, which were defined by their loading configuration and kinematic excitation, namely AI, AIII, AV, BI, BIII, BV, EI, EIII, and EV, were conducted in a virtual environment using SIMWISE 4D. The outcomes of these simulations were recorded, illustrated, and discussed in the subsequent section.

4. Results and Discussion

To study the impact of asymmetries on the lateral vibration of vehicles when passing over a pothole, the lateral vibration time and frequency domain analysis was conducted. The results are presented in this section, categorized by the kinematic excitation. The loading configuration used in the models resulted in a shifting of the Center of Mass (COM) of the sprung mass away from the Center of Geometry (COG) in the lateral direction. The symmetrical loading configuration caused a slight shift of 0.12mm of the COM away from the COG at [0, 0, 0] coordinates. On the other hand, the B loading configuration caused the sprung mass to shift sideways by 5.18mm. This means that symmetrically loaded models with eccentric kinematic excitation can only displace the COM laterally by 2% compared to the B loaded models.

When taking into account the possibility of unforeseen errors or slight displacement of loads from their principle axes during simulations, it was observed that the E load configured models caused a 50% lateral shift in COG compared to the B load configured models. This observation is meaningful as loading the vehicle on the back corner causes a shift in both longitudinal and lateral axes of the COM, whereas for symmetrically loaded models, the vertical COM displacement is dominant. The effect of this observation is further demonstrated in the lateral dynamic responses in the time domain, which are presented in Fig. 3 for the I kinematic excitation.

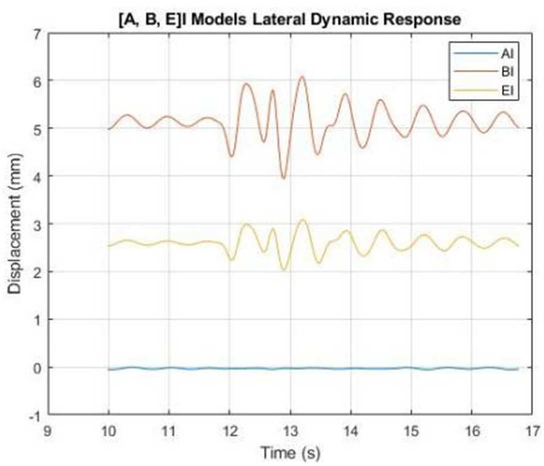

Figure 3: [A, B, E]I Models Lateral Dynamic Time Domain Response

The displacement of the COM from the COG can be observed based on the loading configurations used. Furthermore, the B and E load configurations show high amplitudes of lateral dynamic responses to I kinematic excitation, which can be attributed to the inertia of the sprung mass causing rotational dynamic responses about the longitudinal axis, leading to lateral displacement of the COM. In contrast, the significant lateral dynamic response amplitudes observed in the EI model may be the outcome of the rotational dynamic responses induced by the axis that bisects the longitudinal and lateral axes of the sprung mass.

Thus, as a result of these rotational dynamic responses, the COM shifts laterally due to the distribution of the payloads on one side of the sprung mass and the supporting leaf springs. The damping ratio of the B load configured models was found to be 1.1E-04, while that of the E load configured models was less at 9.2E-05. Furthermore, the AI load configured model showed an insignificant lateral dynamic response under the influence of the I kinematic excitation, as seen in both the time and frequency domain responses presented in Fig. 3 and 4.

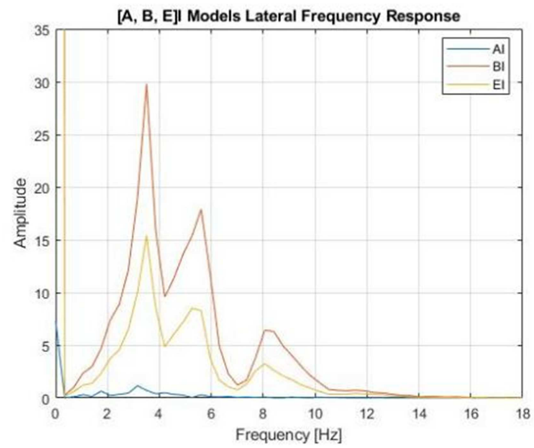

Figure 4: [A, B, E]I Models Lateral Dynamic Frequency Domain Response

The B and E load configured models exhibit high but differing amplitudes at similar frequencies, while the AI models show two distinct frequencies at approximately 1.75 Hz and 3.15 Hz with low amplitudes. Lateral COM dynamic displacements in the AI model could be attributed to unforeseen cases of payloads being laterally displaced during simulation. The B and E load configured models show similar responses at distinct frequencies of 3.50 Hz, 5.61 Hz and 8.06 Hz but with different response signal amplitudes.

These effects may be due to rational dynamic responses dominating the models, resulting in significant lateral dynamic responses. The two distinct frequency signals observed in the AI model could be caused by rotational dynamic responses at around 1.75 Hz and lateral dynamic displacements at 3.15 Hz. The 8.06 Hz, 5.61 Hz, and 3.50 Hz frequency signals could be attributed to the sprung mass's rotational dynamic responses about the longitudinal axis, lateral vibration, and vertical vibration, respectively. These loading configuration effects on the sprung mass's lateral vibration were also examined for the III kinematic excitation and are depicted in Fig 5.

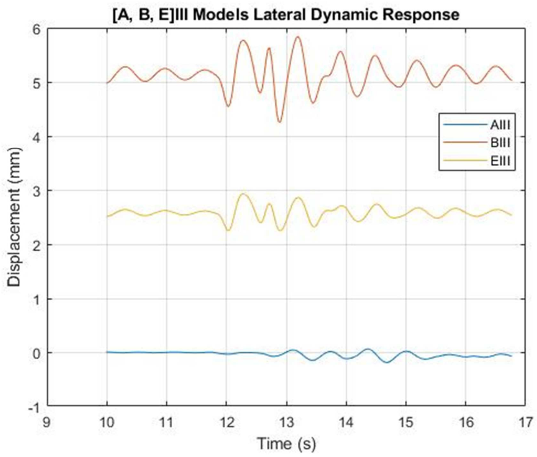

Figure 5: [A, B, E]III Models Lateral Dynamic Time Domain Response

The AIII model displayed slightly higher lateral dynamic response amplitudes and a higher damping ratio of 1.2E-01 compared to the AI model. In the III kinematic excitation, both the EIII and BIII models showed reduced amplitudes and damping ratio of 3.4E-05 and 6.1E-05, respectively, as compared to the EI and BI models.

These difference in damping ratio and amplitudes may be due to the nature of the kinematic excitation, which tends to induce dominant rotational dynamic responses about the lateral axes, thereby reducing the lateral COM dynamic displacements. However, it did not significantly reduce the lateral dynamic displacements of the E and B load configured models, but instead amplified the lateral vibration of the AIII model. These same effects were also observed in the frequency response shown in Fig 6.

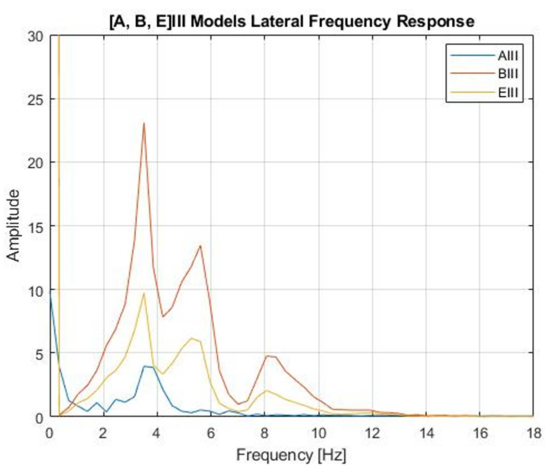

Figure 6: [A, B, E]III Models Lateral Dynamic Frequency Domain Response

The AIII model has a unique response with a distinct frequency of around 2.45 Hz compared to other models affected by the III kinematic excitation. Meanwhile, the B load configured models still show high signal amplitudes at the same observable frequency response signals of 3.50 Hz, 5.61 Hz and 8.06 Hz. In addition, the AIII model does not display any signal responses at 8.06 Hz. This could be because symmetrically loaded payloads do not significantly induce rotational dynamics onto the chassis, but vertical motion due to inertia effects. Thus, the III kinematic excitation appears to have reduced the amplitudes of the sprung mass lateral vibration and influenced the nature of AIII sprung mass's lateral dynamic responses.

In this study, the researchers examined the combined effects of the rotational dynamic response of the front axle and the tandem beam at their respective axes. They found that when one side of the vehicle encounters a pothole on the road, it significantly affects the lateral dynamic response of the sprung mass as measured from the COM. Additionally, the lateral vibration of the sprung mass in this scenario is less damped compared to the other excited A, B, and E models investigated in the study. The damping ratio of the AV, BV, and EV models was found to be high, with values of 1.2E-01, 1.4E-04, and 4.8E-04, respectively, when compared to the I and III kinematically excited A, B, and E models. This is illustrated in Fig 7.

The time-based reactions and virtual motion of the modeled system's parts demonstrate the effects of V kinematic excitation, which is similar in both load configurations. The displacement of the significant sprung mass COM during wheel-pavement interaction shows the dominant lateral motion resulting from the rotational dynamic responses of the unsprung masses to V kinematic excitation.

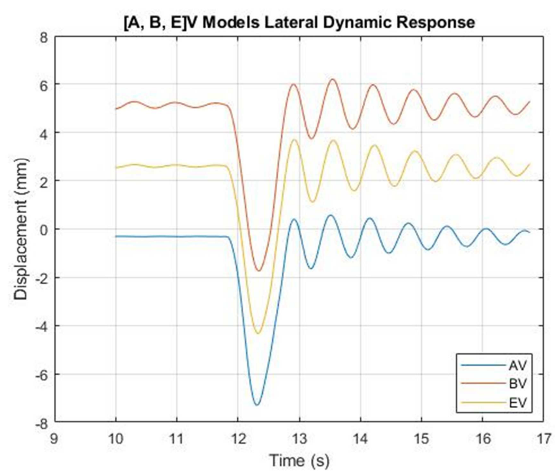

Figure 7: [A, B, E]V Models Lateral Dynamic Time Domain Response

The lengthy decaying sprung mass lateral dynamic responses could be attributed to the combined response of unsprung and sprung masses to V kinematic excitation.

The lateral vibration response of the (A, B, E)V models includes four response signals, as outlined in Table 3.

Table 3
[A, B, E]V Models Lateral Dynamic Response Signal Frequencies

V kinematic excitation					
Frequency [Hz]		3.50	4.56	5.26	5.61
Amplitudes	A	43.23	-	9.34	-
	B	53.02	10.52	-	3.00
	E	52.04	12.15	-	4.20

This is because, orientation of the unsprung masses tends to lower the loads on the leaf springs or wheels, a situation to which the sprung mass tends to respond by rotational and lateral displacements.

Table 3 shows that both models have a shared frequency response signal of 3.5 Hz. However, the AV models have an additional distinct response signal frequency of 5.26 Hz, while the E and B load configured models show two new response signal frequencies of 4.56 Hz and 5.61 Hz. The 3.5 Hz signal response frequency may indicate the less significant vertical vibration of the sprung mass for both models caused by V kinematic excitations.

5. Conclusions and Recommendations

Using SIMWISED 4D, the combined effect of asymmetric loading and eccentric kinematic excitation on the lateral vibration of the sprung mass was estimated and modeled, and the following observations were made:

- Asymmetric loading of the vehicle could significantly shift the centre of mass away from the centre of geometry.
- The nature of the eccentric kinematic excitation of the vehicle wheels has an influence on the nature of the lateral dynamic responses of the vehicle.
- Induced sprung mass rotational dynamic responses tends to amplify the lateral vibration of the vehicle.
- Lateral vibration of the sprung mass is dominant in the B and E asymmetrically loaded and V kinematically excited vehicles.

Further mathematical models of vehicles having dependent axle configurations should be established to further investigate and validate the effects of center of mass shifting away from the center of geometry. The models established in this study may be useful in contributing to an understanding on the vehicle dynamics especially in cases of critical accidents analysis.

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