Journal of Research in Engineering and Applied Sciences

EFFECTS OF LOADING MASS ECCENTRICITIES ON UNSPRUNG MASS ROTATIONAL DYNAMIC RESPONSES OF HEAVY VEHICLE ON IRREGULAR ROAD PAVEMENT

[1]Josua K Junias [2]Fillemon N Nangolo [3]Petrina T Johannes
[1]Mechanical and Metallurgical Engineering, University of Namibia, Namibia;
[2]Mechanical, Industrial and Electrical Engineering, Namibia University of Science and Technology, Namibia;
[3]Civil and Mining Engineering, University of Namibia, Namibia
Email: {[1]josuakjunias@gmail.com, [2]fnangolo@nust.na, [3]pjohannes@unam.na}

Abstract

Using individual independent unsprung masses in suspension system modelling is not a realistic reflection of vehicle dynamics in response to eccentric wheel kinematics and asymmetric heavy vehicle loading. This is because the use of such masses does not accurately represent the unsprung mass system's influence on heavy vehicles' dynamics, including its impact on the sprung masses or wheel pavement dynamic loading. This study aims to examine how heavy vehicle asymmetric loading and wheels' eccentric kinematic excitation affect the rotational dynamic response of the unsprung masses. A total of 450 models were used to investigate various asymmetrical cases, from which 9 3D 24 DOF heavy vehicles' 4 DOF rear tandem drive axle suspension systems were selected for analysis using SIMWISE 4D. These vehicles were tested for a pothole depth of 25 mm and vehicle translational speed of 60 km/h. The study found that the nature of the pavement distress factor (kinematic excitation) determines the suspension's rotational dynamic response and, consequently, the sprung mass. Moreover, the load distribution on the sprung mass also affects the rotational dynamic response of the tandem beams.

Key Words - Mass eccentricities, unsprung mass, rotational dynamic response, dependent axle, irregular road pavement.

1. Introduction

Researchers may not have given top priority to comfort in high cargo vehicles, which could explain why a significant number of these vehicles still use front rigid axle suspension. This type of suspension has wheels attached to the hub that rotate on non-fictional hubs on the steering spindle and steering knuckles, as seen in the Hendrickson STEERTEX NXT front steer axle with integrated suspensions. However, several independent rear suspension designs have been developed, such as tandem drive axles that allow for independent wheel motion in response to pavement irregularities. Another conventional design is the RT/RTE steel leaf spring rear suspension with walking beams, which can be integrated into heavy vehicles' tandem drive axles. These suspension systems support the vehicle body, act as structural members, and absorb shock loads, making them widely used in heavy vehicles that carry axial and lateral loads.

Integrating these suspension components with the sprung mass can add a realistic element to modelling heavy vehicle vibration responses. This study defines general asymmetry through a combination of asymmetrical load distribution on the sprung mass and eccentric kinematic excitation of the heavy vehicle wheels. The study observes the influence of irregular road profiles on the wheel's kinematic excitation and the impact of asymmetrical loading configurations on the vibration response of the sprung mass at the rear axle. The next section of the study will review the relevant literature and present the virtual models developed to assess the rotational dynamics of the rear axle suspension system. The results will then be presented and discussed to draw conclusions.

2. Revised Literatures

Virtually, leaf springs (with leaves made of composite materials) have been modelled using SOLIDWORKS or Pro-E and analyzed using ANSYS as in [1]. Further, several other literatures such [2] had investigated the leaf springs stiffness for different chassis masses, have utilized virtual 3D leaf spring models to predict the leaf springs stiffness. Reference [3], among other researchers, have illustrated the differences in dynamic responses of the mono and multi-leaf spring models governed by a dynamic simulation equation of motion incorporating the damping effects in addition to stiffness study. This indicates that virtual 3D leaf springs models could be useful in mechanical system vibration studies. It is worth noting that a model that is equivalent to the elliptical leaf spring was established by [4] to mechanically represent the suspension system of the simplified modelled vehicles. It fundamentally defined the means of incorporations onto virtual multi-dimension and multiple degree of freedom vehicle models. It is then crucial to mention that suspensions filters and attenuates the vibration transmitted, hence reduces the dynamic load harmful effects onto the sprung mass [5]. As research works advances, it would be needed to establish detailed equivalent leaf springs to showcase realism in developed virtual models.

Most virtual and mathematical models that are developed to investigate the effects of road conditions on vehicle tires, are either presented with unsprung masses as simplified individual components suspending the sprung mass. These cases have been noted on most accepted 2DOF quarter car models, 4DOF half and 7DOF full car models, as utilized by researchers such as [6] and several other literatures. Further, based on the same approach, MDOF models were also established to investigate means of controlling sophisticated dynamic responses of several vehicle constituting components motions such as yaw and roll motions while focusing on wheels' interactions with the deteriorated pavement. In these models, assumptions had been made that wheels are always in contact with the pavement and suspends the rigid lumped vehicle body. This approach could be the same as that utilized in moderate MDOF models as those of 14 DOF vehicle model composed of the 7 DOF ride vehicle and the 7 DOF handling models. Arguably, usage of individual independent unsprung masses does not seem to truly reflect the dynamic responses of the unsprung mass system on heavy vehicles hence their influential dynamic inputs onto the sprung masses or wheel pavement dynamic loading.

Even though all these models depicted a fundamental mean of mathematically and virtually presenting a full car vehicle, they do not incorporate the interaction influence of the unsprung mass to the sprung mass or the pavements. Further, very little literatures have investigated the combined effects of general eccentricities on heavy vehicles suspensions responses. This study aims at investigating the rotational dynamics of the 3D 4DOF rear tandem drive axle suspension of the translating 24 DOF 3D heavy vehicle model. These models are eccentrically loaded and kinematically excited at a pothole depth of 25mm at 60km/h moderate drive speed. Also, they incorporate asymmetrically elastic and dissipative properties distribution on them.

Wheel loads onto pavements could be irregular hence no static or dynamic load is evenly distributed on both wheels on a given loaded axle. This case is supported by [7] judgements on contradicting earlier suspension analysis works by [8] that there could be a tendency of unequal instantaneous axle forces on an axle group due to road profile generated dynamic forces. Even though [9] have investigated the effects of driving conditions and suspension parameters on longitudinal-connected air suspension dynamic load sharing using a similar tri-axle semi-trailer, they have also indicated that the dynamic coefficient is not always in accordance to with the dynamic load sharing coefficient. This simply implies that, similarly, the rotational dynamic responses of the tandem beam (walking beam) could influence the dynamic rotation of the axle in response to the dynamic forces applied onto wheels by the road profile. Moreover, despite the unsprung mass centre of mass vertical vibration that is mostly investigated and has been monitored to influence the sprung mass dynamic responses damping, rotation dynamic response of unsprung masses could also influence the damping and amplification of the sprung mass rotational dynamic responses especially in cases of asymmetric sprung mass load distribution.

Multiple factors including the changes in sprung and unsprung masses affects the vibration responses of the vehicle differently. Reference [5] investigated these effects by varying the sprung mass at constant proportional unsprung mass and vice versa. They had found that, respectively, the optimum damping coefficient increases at an unaffected acceleration root mean square as compared to an increase in the root mean square value for a given unsprung mass at constant sprung mass. Interestingly, fixing the unsprung mass influences the damping coefficient and the accelerations simultaneously. This points to a very pivotal point of doubling the quarter car model sprung mass and adding an additional unsprung mass-spring system to define the half car model or rather doubling the half car model to define the full car model as utilized in [10], [11] and [12] literatures. Based on their approach, the unsprung vertical dynamic response of the model developed in [13] could be used to compare this studies' developed model's rear axle vertical dynamic responses. In this study, thereafter, the rotational dynamics of the tandem beam and spindles will be conducted to extend the present analysis on unsprung mass rotational dynamics hence to tend to form a foundation for mathematical modelling of unsprung masses rotational dynamics. Conclusions were derived from this study upon evaluating and discussing the results obtained from the virtual model presented in the first two upcoming sections.

3. Virtual Model

A good suspension system should ensure that a vehicle is stable, safe, and comfortable while driving on rough road surfaces. In order to meet these demands, many studies, such as [13], have examined the performance of passive, semi-passive, and active suspension systems in response to road irregularities on quarter car models. These studies aim to demonstrate the effectiveness of suspension systems in reducing the impact of road irregularities. In this particular study, a simplified model of the Hendrickson RT/RTE steel leaf spring rear suspension with walking beams was developed using two simple beams connected to the spindle ends with a collision constraint. This allowed the two beams to independently orient around the spindle while also being able to orient with the spindle around its center of mass. The conventional leaf springs were simplified using equivalent 3D mass spring leaf spring models as defined in [4].

Illustratively, Fig. 1 indicates the simplified rear suspension while Fig. 2 shows the utilized 3D equivalent mass spring leaf model used in the model.

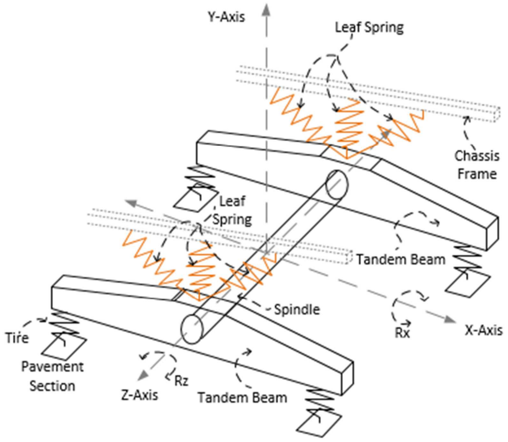

Figure 1; Simplified Hendrickson RT/RTE steel leaf spring rear suspension

It is important to note that this study only focuses on the rear suspension system, and the data presented in the results and discussion section is obtained from a full 3D, 18 or 24 DOF model that utilizes this suspension system. In this model, the transverse and longitudinal motions of the spindle are constrained using a cylindrical joint on a vertical slot, which allows for vertical movement. In Fig. 1, Rx and Rz represent the rotation of the spindle and tandem beams around the X and Z axes, respectively. The leaf springs shown in Fig. 1 are designed using the concept described in Fig. 2, which is based on the work of [4].

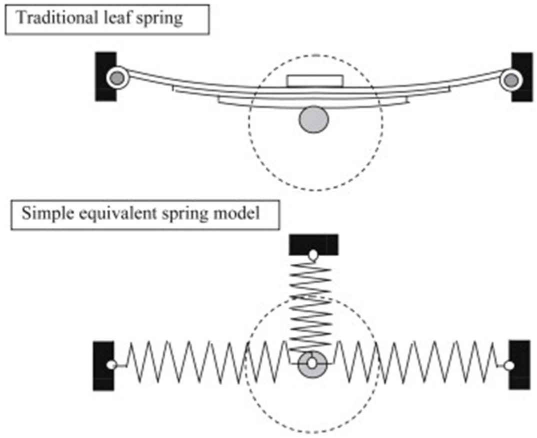

Figure 2 : Traditional leaf spring versus Simple equivalent spring model [4]

In this study, symmetrical cases in vehicle dynamics are defined based on symmetrical load distribution on the sprung mass (Loading type A) and homogeneous interaction of the vehicle wheels with the road profile (kinematic excitation I). The load distribution on the sprung mass can also be varied for full car models, with concentration along the longest edge of the sprung mass (loading type B) or all along the shortest edge, meaning all at the back of the full car model (loading type E). For these loading types, the wheels can be eccentrically excited in various ways. For example, only the wheels at the back of the full car model encounter potholes (kinematic excitation III), or only the left (or right) wheel and the left (or right) back front (or back) wheel encounter potholes at the same time (kinematic excitation V). These eccentricities will be used to investigate the effects of general asymmetries on the rotational dynamic response of the spindles and tandem beams, as well as their influence on the vertical dynamic response of the sprung mass. The results will be discussed, followed by conclusions and recommendations for further studies on certain aspects considered in this study.

4. Results and Discussion

To begin with, the vertical vibration of the rear axles, as displayed in Fig 3 and 4, shows the impact of variations in loading configurations. While the effects are not as significant as those on the sprung mass, they do play a role in determining the overall sprung dynamic responses and the distribution of pavement loading forces on the tires. As a result of symmetrical kinematic excitations applied to all wheels, Fig 3 illustrates the effects of load distribution on the sprung mass on the vertical dynamic response of the unsprung mass. When payloads are distributed along the longest edge of the heavy vehicle loading bed, the dynamic responses of the unsprung mass vertical displacement are similar to those when the load is concentrated on one back corner of the loading truck bed. Both models exhibit a significantly lower centre of mass (COM) of the unsprung mass.

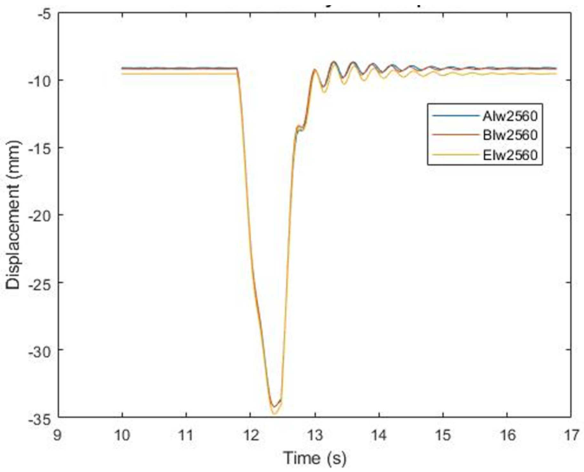

Figure 3 : Rear Axle Vertical Dynamic Response [I Excitations]

Further, high amplitudes of rotational motions of the unsprung mass in response to the applied kinematic excitation is observable in Fig. 4.

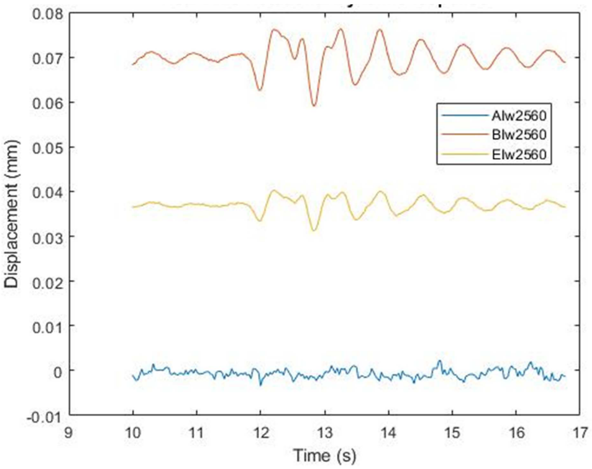

Figure 4 : Rear Axle Rotational Dynamic Response [I Excitations]

In Fig. 4, it is evident that high amplitudes of rotational motions of the unsprung mass occur in response to the applied kinematic excitation. The static orientations of the rear axles have been indicated to shift significantly at about 0.068 and 0.036 degrees for the B and E load configurations, respectively. Additionally, for these load configurations, high rotational response amplitudes are noticeable, which have relatively low decaying and lengthy settling time in comparison to the AIw2560 model. Unlike the AIw2560 model, which showed very low responses to the kinematic excitations, it maintained a near-zero static orientation throughout the study period. Fig. 5 also shows a similar situation in the III kinematic excitations.

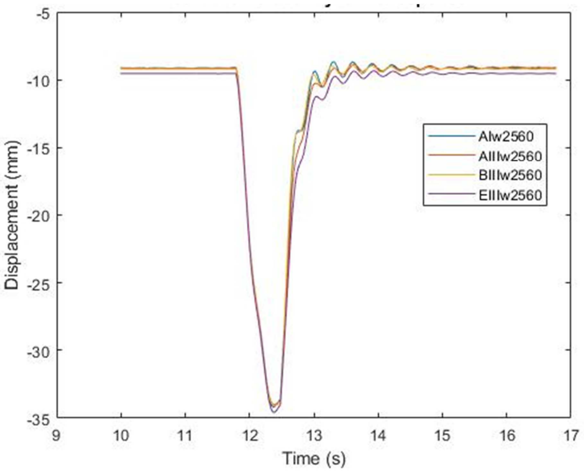

Figure 5 : Rear Axle Vertical Dynamic Response (III Excitations)

In Fig. 6, the *III* kinematic excitations tends to have introduced rotational dynamics responses on the *AIIIw2560* model, that tends to follow a governing overall dynamic response as compared to the *AIw2560*.

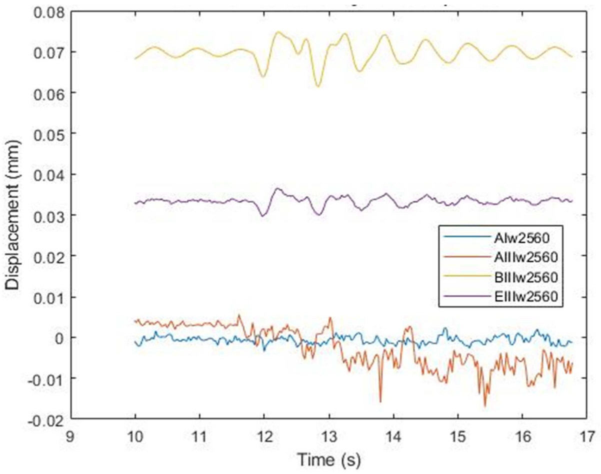

Figure 6 : Rear Axle Rotational Dynamic Response (III Excitations)

One could suggest that these responses are influenced by the uniform distribution of payloads on the sprung mass, which is located slightly towards the rear of the vehicle models. As a result, the III kinematic excitations appear to generate rotational dynamic responses in the sprung mass that may govern the rotational dynamic response of the rear axle suspension shown in Fig. 6. Similar rotational dynamic response characteristics can be observed in the rear axle suspension of the B and E load configured models compared to those caused by the I kinematic excitations. Interestingly, the V kinematic excitations appear to have a diminishing effect on the rotational dynamic responses of the rear axles, as shown in Fig. 7.

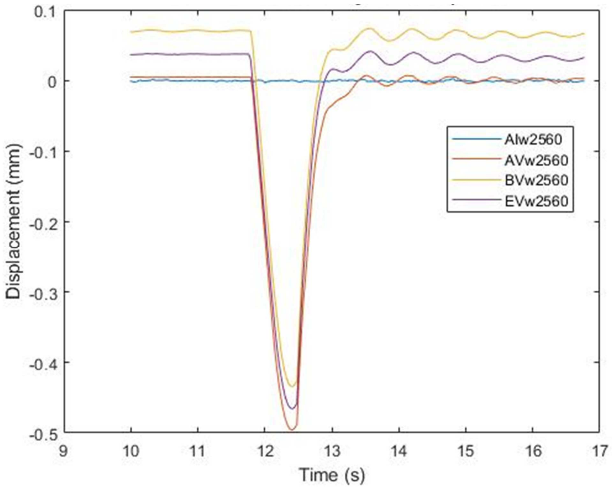

Figure 7 : Rear Axle Rotational Dynamic Response (V Kinematic Excitation)

Furthermore, the V kinematic excitation results in significant vertical displacement and rotational effects on the rear axle during the time of the excitation. This is likely due to the fact that the axle rotates significantly when only one wheel encounters a 25 mm deep pothole, causing the tandem beams to rotate and lowering the axle on one side. When compared to the control model, a significantly higher rotational motion is observed on the V kinematically excited models, regardless of the loading configuration. Additionally, Fig. 8 indicates that the V kinematic excitation leads to a noticeable decrease in the vertical displacement dynamic responses of the E and B load configured models as compared to the control model AIw2560.

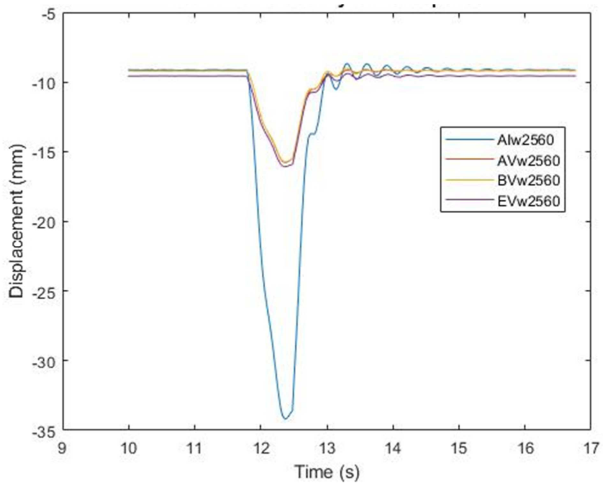

Figure 8 : Rear Axle Vertical Dynamics Response (V Excitations)

What this could reveal is that, a single pothole on a pavement could have significant impact on the lateral and longitudinal dynamic response of the vehicle.

The vertical and rotational dynamic response of the axle is being influenced by the rotational dynamic response of the tandem beams respectively. This would mean that the results showcased in Fig. 4 could be highly influenced by the rotational dynamic response indicated in Fig. 9.

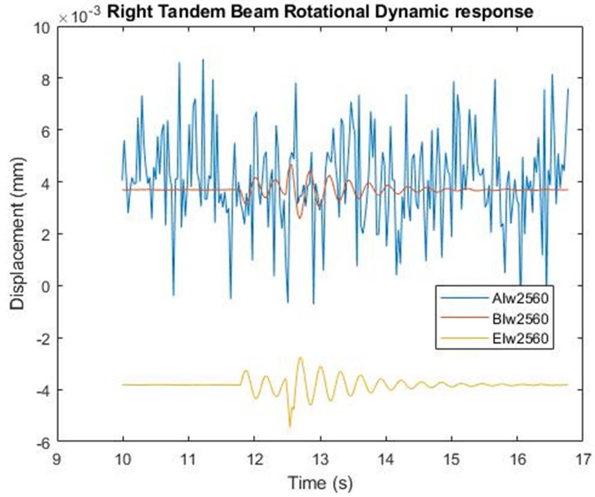

Figure 9 : Right Tandem Beam Rotational Dynamic Response (I Excitation)

Comparing the *AIw2560* model right tandem beam rotational dynamic responses in Fig. 9 and 10, steady motion response (with less settling time) of the tandem beams is observable on the *E* and *B* load configured models after the wheels has encountered the potholes.

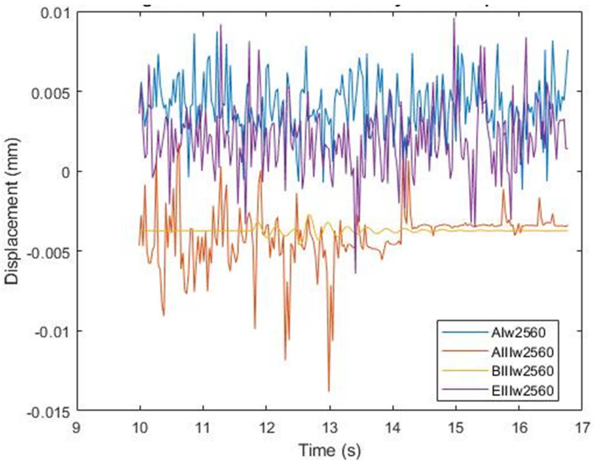

Figure 10 : Right Tandem Beam Rotational Dynamic Response (III Excitation)

The data presented in Fig. 3, 4, and 9 provide insights into the multi-axial dynamic response of the suspension system. However, these responses are often overshadowed by the commonly accepted analysis of the vertical dynamic response of the independent unsprung mass. It is important to note that the tandem beam rotates during and after encountering a pothole, as seen in the B and E load configuration models. The rotational dynamic responses in the A load configured III excited model are affected by a vibration signal generated from the sprung mass dynamic motion, while the B load configured III model shows steady responses before the kinematic excitations and less settling time. Similar behavior is observed in the E load configured models under the influence of the III kinematic excitations.

Furthermore, a study conducted on the left tandem beam of the suspension model used in this research has shown that the III and V kinematic excitations have a significant impact on the rotational dynamic response of the suspension system. These responses could provide further explanation as to why the E load configured models tend to have a relatively steady rotational dynamic response before and after the kinematic excitation. This is observable in Fig. 11.

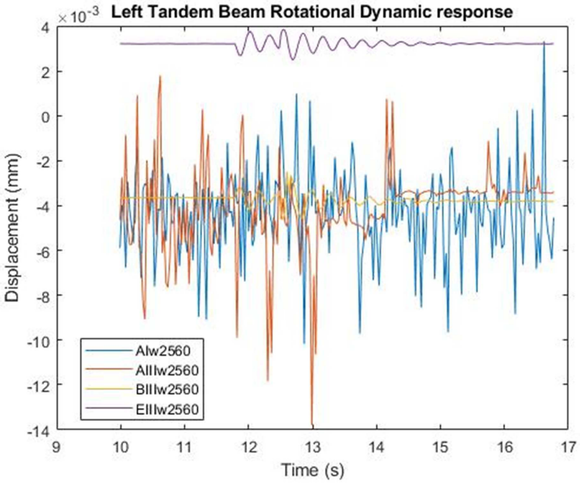

Figure 11 : Left Tandem Beam Rotational Dynamic Response (III Excitation)

The response of the B load configured model is similar to that of the EIIIw2560 model in terms of rotational dynamics. The distribution of load on the sprung mass explains this similarity. Fig. 11 shows that the B load model has slightly lower response amplitudes than the E load model, which also has a slightly higher static orientation than all other models. Furthermore, the right tandem beam, where the load is concentrated, is affected by the dynamic response of the sprung mass, leading to less settling time and moderate amplitudes, as shown in Fig 10. Additionally, Fig. 12 still shows a critical situation caused by the V kinematic excitation.

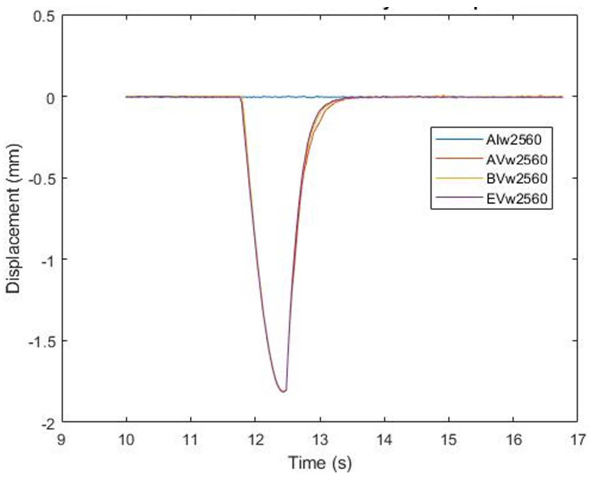

Figure 12 : Left Tandem Beam Rotational Dynamic Response (V Excitation)

The V kinematic excitation, which simulates a deep pothole, does not induce significant dynamic responses in any of the models. Fig 12 highlights the difference in effects between the I and V kinematic excitations, providing insight into the vibrations caused by potholes on vehicle components.

5. Conclusion and Recommendation

A 3D virtual suspension model with 7 degree of freedom was created to investigate the impact of pavement distress factor, specifically a 25 mm pothole depth, on the rotational dynamic response of the unsprung mass. The study aimed to provide a foundation for milt-axial suspension modelling. The results indicated that;

- The axles rotational dynamics response is influenced by the pavement profile and the multi-axial dynamics responses of the sprung mass.
- Load distribution on the sprung mass affects the rotational dynamic response of the tandem beams.
- Eccentric kinematic excitations have high influences on both the vertical and rotational dynamic responses of the axle, as well as on the rotational dynamic response of the tandem beam.

Based on these findings, further motion simulation studies should be conducted in different virtual environments and with varying pavement profiles and heavy vehicle translational speeds to gain a full understanding of the effects of asymmetric loading and eccentric kinematic excitations. Additionally, a comparable 7 DOF mathematical model should be developed to validate the results of this study.

Acknowledgement

We highly appreciate the department of Mechanical and Metallurgical Engineering at the University of Namibia for the technical assistance rendered in the realization of this study. This work forms part of a Master study undertaken at the University of Namibia.

References

[1] M. M. Patunkar and D. R. Dolas, "Modelling and Analysis of Composite Leaf Springs under Static Load COndition by Using FEA," *International Journal of Mechanical and Industrial Engineering,* no. 1, pp. 1-4, 2011.

[2] A. O. Mohamed, A. S. Ahmed, M. Aki, L. Wei-Yi and B. Rena, "Multibody System Modelling of Leaf Springs," *Journal of Vibration and Control,* pp. 1601-1638, 2004.

[3] V. Karthik and V. Chandan, "Modeling and Simulation of Composite Mono Leaf Spring," *International Journal of Engineering Research & Technology (IJERT),* 2015.

[4] B. Mike and H. Damian, "Modelling and Assembly of teh Full Vehicle: Modelling leaf springs," in *The Multibody Systems Approach to Vehicle Dynamics (Second Edition)*, Coventry, Butterworth-Heinemann, 2015, pp. 451-533.

[5] A. Yudianto, N. Kurniadi, I. W. Adiyasa and Z. Arifin, "The Effects of Masses in the Determination of Optimal Suspension Damping Coeficient," *Journal of Phsyics: Conference Series,* 2019.

[6] M. K. Mahala, P. Gadkari and A. Deb, "Mathematical Models for Designing Vehicels for Ride Conformt," in *2nd International Conference on Research into Design*, 2009.

[7] E. D. Llyod, "Heavy Vehicle Suspension-Testing and Analysis," School of Built Environment and Engineering-Queensland University of Technology, Queensland, 2010.

[8] P. F. Sweatman, "Effects of heavy vehicle suspension on dynamics roads loading. Research Report ARR 166," Australian Road Research Board (ARRB), Vermont South, Victoria, 1980.

[9] C. YiKai, H. Jie, K. Mark, C. WuWei and Z. WeiHua, "Effect of driving conditions and suspension parameters on dynamcis load-sharing of longitudinal-connected air suspensions," Scienc China Technological Sciences, pp. 666-676, 2013.

[10] R. Mahmoud and B. Atanu, "Passive Suspension Modelling and Analysis of a Full-Car Model," International Journal of Advanced Science and Engineering Technology, pp. 250-261, 2013.

[11] T. P. Turakhia and M. J. Modi, "Mathematical Modelling and Simulation of a simple Half-Car Vibration Model," International Journal for Scientific Research & Development (IJSRD), pp. 2321-2613, 2016.

[12] M. H. G. A. A. N. Ammar, "Modeling, Simulation and COntrol of Half-Car Suspension using Matlab/Simulink," International Journal of Science adn Research (IJSR), pp. 2319-7064, 2018.

[13] P. Sathishkumar, J. Jancirani, J. Dennie and S. Manikandan, "Mathematical modelling and simulation of quarter car vehicle suspension," International Journal of Innovative Research in Science, Engineering and Technology, pp. 1280-1283, 2014.