Modeling and Validation of 7-DOF Ride Model for Heavy Vehicle

Syabillah Sulaiman, Pakharuddin Mohd Samin, Hishamuddin Jamaluddin, Roslan Abd Rahman, Mohammad Safwan Burhaumudin

***Abstract*—**This paper presents the modeling and validation of a 7-degree of freedom (DOF) full vehicle model to study ride performance of a heavy vehicle. To improve suspension control system that can reduce roll over effect and improve ride comfort, dynamic modeling of passive heavy vehicle model was constructed. Such simulation model was developed in MATLAB Simulink software. Several assumptions related to 7-degree of freedom modeling were made and stated in this paper. This heavy vehicle model was validated using vehicle dynamics simulation software known as TruckSim. The validation was done by comparing the simulation results. A ride test was conducted at two different speeds, and the simulation results consist of roll angle, pitch angle, and vehicle body displacement are analyzed.

***Keywords*—**Heavy vehicle, MATLAB/Simulink, Ride Model, Validation Model

I. INTRODUCTION

A heavy military heavy vehicle that transports troops needs high vehicle stability, ride comfort and road friendliness [1], [2]. This heavy vehicle is regularly driven on different terrains [3], and thus the stability of the vehicle needs to be studied to improve the vehicle ride performance [4], [5]. This simulation model was validated with vehicle simulation software to represent the vehicle's ride behavior. This approach was similarly adopted by other researchers [6]-[10].

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There are three types of model commonly used to represent vehicle suspension behavior. These are quarter-car model [11], half car model [12], [13] and full car model [14]-[16]. In this paper, a full car model was used to investigate the ride performance behavior of a heavy vehicle. The full car model is a linear 7-degree of freedom consists of a sprung mass that is connected to unsprung mass. Unsprung mass consists of four suspensions and four tires located at each corner of the body. The sprung mass has 3-degree of freedom representing body bounce, roll and pitch movement, while the unsprung masses has 4-degree of freedom in vertical motions [17], [18].

The heavy vehicle model was constructed in MATLAB Simulink and was validated by using heavy vehicle simulation software known as TruckSim.

This paper presents the heavy vehicle ride model validation based on the developed 7-degree of freedom full vehicle model for ride model simulation and the results are compared with heavy vehicle simulation software.

II. MATHEMATICAL MODELING

The heavy vehicle ride model in this study is based on a four wheels vehicle. The ride model consists of 7-degree of freedom which involves vehicle body bounce, pitch, roll, and four wheels vertical motions. Fig. 1 shows the vehicle ride model.

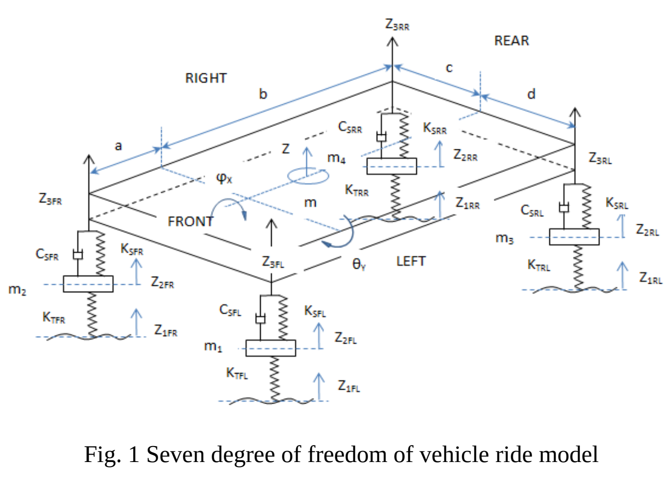

Fig. 1 Seven degree of freedom of vehicle ride model

There are some assumptions made in this study. The vehicle aerodynamic effect is neglected and the road is assumed to be level except for road disturbance. The vehicle is also assumed to be rigid where the load transfer from one point to another is hundred percent effective. Parameters of the vehicle are also assumed to be constant throughout the simulation process such as tire stiffness, spring stiffness, and damper coefficient.

Based on the 7-degree of freedom model in Fig. 1, the displacement of sprung mass is defined by:

$$m_B \ddot{Z}_B = -F_{SFL} - F_{DFL} - F_{SFR} - F_{DFR} - F_{SRL} - F_{DRL} - F_{SRR} - F_{DRR} \quad (1)$$

where m_B is the mass of the vehicle, $\ddot{Z}_B$ is the body acceleration and F is the force acting on vehicle model(S for spring, D for damper, FL for front left, FR for front right, RL for rear left, RR for rear right). The spring forces, F_{Sij} (i for front or rear and j for left or right) that act on the suspensions are given by:

$$F_{Sij} = K_{Sij}(Z_{Bij} - Z_{Uij}) \quad (2)$$

where Z_{Bij} is the sprung vertical displacement, Z_{Uij} is the unsprung mass vertical displacement and K_{Sij} is the suspension spring stiffness. Then the damper forces, F_{Dij} of the suspensions are given by:

$$F_{Dij} = C_{Sij}(\dot{Z}_{Bij} - \dot{Z}_{Uij}) \quad (3)$$

where $\dot{Z}_{Bij}$ is the sprung vertical velocity, $\dot{Z}_{Uij}$ is the unsprung mass vertical velocity and C_{Dij} is the suspension damper coefficient. Acceleration at unsprung mass is given by:

$$m_{Uij}\ddot{Z}_{Uij} = F_{Sij} + F_{Dij} - F_{Tij} \quad (4)$$

where m_{Uij} is the unsprung mass, $\ddot{Z}_{Uij}$ is the vertical acceleration at unsprung mass and F_{Tij} is the dynamic tire forces. Dynamic tire forces, F_{Tij} is defined as:

$$F_{Tij} = K_{Tij}(Z_{Uij} - Z_{Rij}) \quad (5)$$

where K_{Tij} is the tire stiffness and Z_{Rij} is the road profile where the disturbance on the road act. The pitch effect of the vehicle is given by:

$$\begin{aligned} J_y\ddot{\theta} = &-(F_{SFL} + F_{DFL} + F_{SFR} + F_{DFR})a \\ &+ (F_{SRL} + F_{DRL} + F_{SRR} + F_{DRR})b \end{aligned} \quad (6)$$

where J_Y is the moment of inertia about x-axis and $\ddot{\theta}$ is the pitch acceleration, while a is the length of vehicle from the center of gravity to the front end and b is the length of vehicle from the center of gravity to the rear end of the vehicle. The roll effect of the vehicle can is given as follows:

$$\begin{aligned} J_x\ddot{\varphi} = &-(F_{SFL} + F_{DFL} + F_{SRL} + F_{DRL})c \\ &+ (F_{SFR} + F_{DFR} + F_{SRR} + F_{DRR})d \end{aligned} \quad (7)$$

where J_X is the moment of inertia about x-axis and $\ddot{\varphi}$ is the pitch acceleration, while c is the length of the vehicle from the center of gravity to the right end and d is the length of vehicle from the center of gravity to the left end of the vehicle.

III. Method of Model Simulation

Simulation of the heavy vehicle model was conducted by using Simulink. The model was then validated with heavy vehicle multi body dynamics software, TruckSim. A ride test was conducted for both simulations. The road profile as the disturbance was applied on the left tires and followed by the right tires for both simulations. The height and length of the bumps is 0.1 m (incremental elevation) and 5 m (station) respectively for both sides, as shown in Fig. 2.

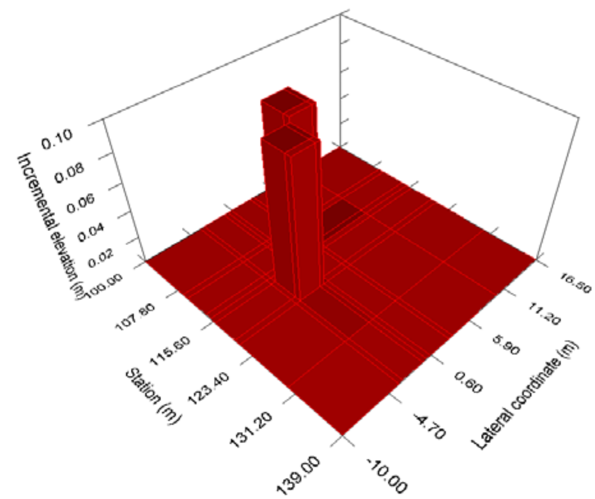

Fig. 2 Road disturbance profile

Fig. 3 shows graphically the arrangement of the bumps and the vehicle movement when it hits the bumps. The left and the right bumps were arrange such that the change in the direction of disturbance occurs instantaneously.

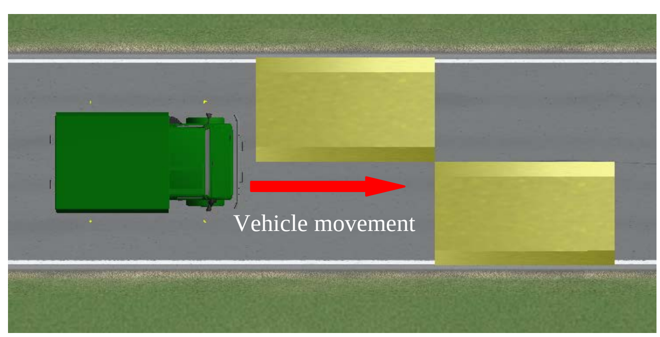

Fig. 3 Ride test road profile

A. Simulink Model

Fig. 4 shows the Simulink block diagram of the ride model. The road profile disturbance acts on the unsprung mass system. The signal from unsprung mass block diagram namely suspension tire forces are transmitted to the sprung mass, pitch, and roll block diagram to compute the output variable. Then the output from sprung mass, pitch, and roll are fed back to the unsprung system.

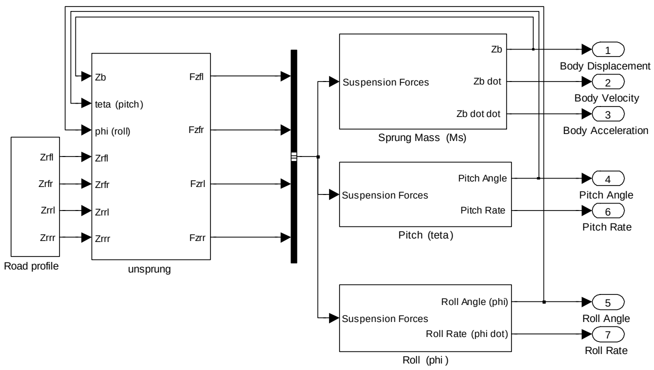

Fig. 4 Simulink block diagram

The output variable namely pitch, roll, and sprung mass displacement are recorded and compared with TruckSim simulation results. All parameters of the vehicle are assumed constant throughout simulation.

B. TruckSim Model

The same source of road disturbance applied in Simulink simulation is used by the TruckSim. The heavy vehicle parameters are defined using the TruckSim user interface. These are, spring, damper, tire, track width, vehicle length, unsprung and sprung masses, moment of inertia at *x* and *y*-axes. Fig. 5 shows the user interface for the input parameters to be defined for the heavy vehicle that are used in the simulation in TruckSim.

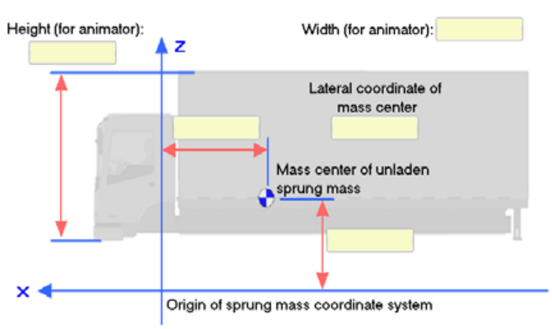

Fig. 5 User interface for heavy vehicle

IV. Results of Simulation and Discussion

A. Simulation: 36 km/h

The performances of the simulation models studied are in terms of pitch, roll, and vertical displacement responses are compared between Simulink and TruckSim simulation models. The road profile as shown in Fig. 2 was used as the road disturbance. The speed of the vehicle model is kept constant throughout the simulation that is 36 km/h.

Figs. 6 to 8 show the simulation results of both Simulink and TruckSim performances when passing through the external disturbance. The vehicle hits the first bump at 5 second on the left side and hit the second bump at 5.6 second on the right side.

Figs. 6 and 7 show the Simulink and TruckSim simulation have similar trend but slightly different in magnitude. Fig. 8 shows the simulation result of Simulink body displacement which has the same trend as TruckSim simulation but a slight different in magnitude. This error maybe due to simplified model used in Simulink, while TruckSim model that is based on the actual tested vehicle simulation process thus becomes more precise.

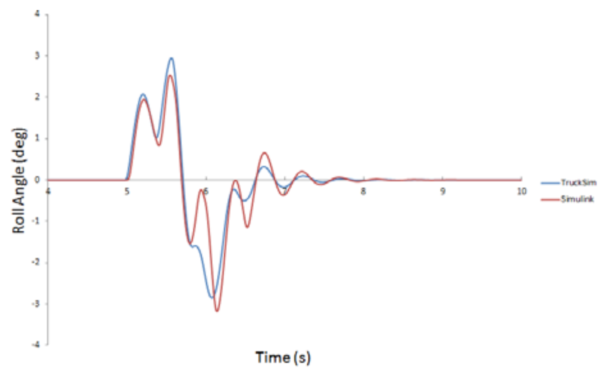

Fig. 6 Roll angle response at 36 km/h

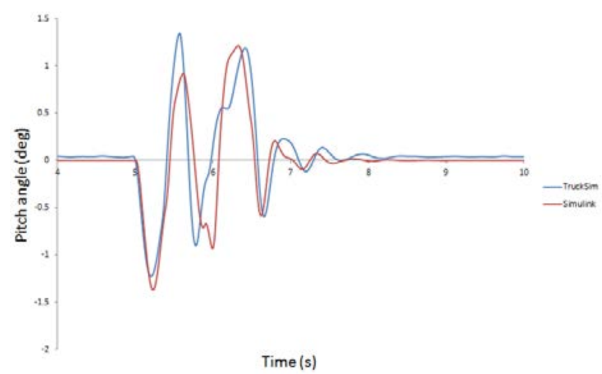

Fig. 7 Pitch angle response at 36 km/h

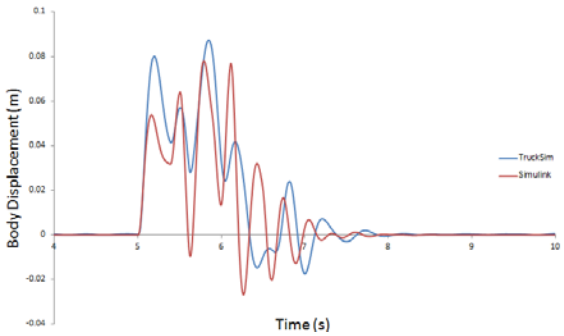

Fig. 8 Body displacement response at 36 km/h

B. Simulation: 43 km/h

The result of the simulation at 43 km/h show similar trend of roll angle, pitch angle, and body displacement between Simulink and TruckSim. These are shown in Figs. 9 to 11. The time taken to hit the first bump is a bit faster compared with the first simulation, because the speed of the vehicle is faster. The time taken to hit the first bump for 43 km/h is about one second faster than 36 km/h.

The different vehicle speed used in the simulations is to show that the trend of the output of the simulink model is consistent with independent speed. Figs. 9 to 11 show similar trends of the speed at 36 km/h are observed.

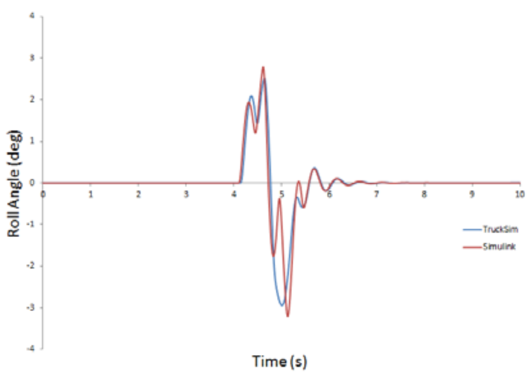

Fig. 9 Roll angle response at 43km/h

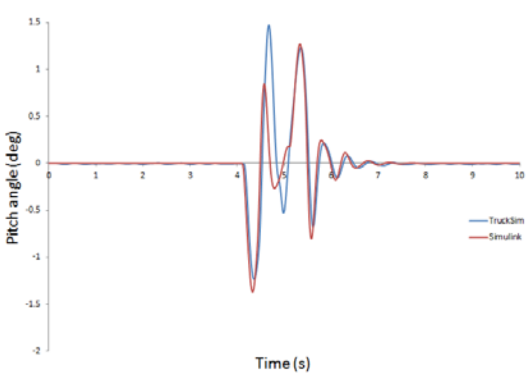

Fig. 10 Pitch angle response at 43km/h

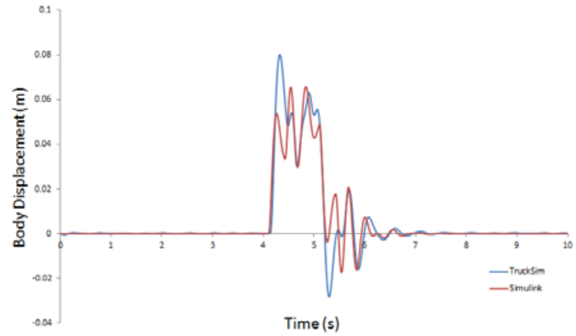

Fig. 11 Body displacement response at 43km/h

V. Conclusion

The heavy vehicle with passive suspension system consists 7-degree of freedom ride model has been developed and validated. This passive vehicle model was constructed in Simulink and compared with the multi body dynamics software known as TruckSim. These comparisons were made to validate the Simulink model.

These models were validated by simulating the models at different speeds, these are 36 km/h and 43 km/h, with an identical road disturbance. The simulations were made to compare the results of the Simulink model with the TruckSim model. Graph of roll angle, pitch angle, and vertical displacement of vehicle body were recorded from the simulations. The simulation results of the Simulink shows similar trend as TruckSim, but has an error in magnitude. It is possibly due to simplified model in Simulink, even though this model has considered a 7-degree of freedom of full vehicle model. The significant observation is, the trend of the vehicle movement when it hits the bumps, the related performance must have the same trend even at different speeds. Similar trends between Simulink and TruckSim model indicate that the Simulink model can be used for further research to study heavy vehicle ride performance.

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