

# Steering test of mid-size bus with flexible-body dynamics model

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**Abstract.** The object of this paper is to analyze the vehicle structural vibration responses during the step steering simulation test. With computer simulations, confirming the influence from the difference between configurations of components on mid-size electrical bus and tradition one could be possible. The difference of the vibration responses between flexible multi-body model and rigid one would be discussed. Since the wheel base of mid-size bus is longer than passenger car, the deformation of vehicle body more obviously influences the output of vibration response. The operating condition in practical driving can be expressed by flexible model, and the performance prediction of vehicle can be closer to the real vehicle behavior. The difference between the flexible body simulation and rigid body simulation is 1.17%, and the flexible body model is more practical.

## 1 Introduction

The design requirements of vehicle handling and comfort are considerably important in the field of vehicle design. The major reason is the safety of driver and passengers, and followed by the driving quality of the vehicle. In order to reduce development time and cost, the prediction of the dynamic characteristics of the designed vehicle is required, so vehicle mathematical model which supports the scientific theory to evaluate the traffic safety and quality of vehicles should be established. With the advance of modern computer, computer-aided engineering (CAE) is applied to the vehicle mathematical model.

In 2014, the worldwide sale of global electric and hybrid buses is accounted for 5.6% of total buses sales, and it is expected to reach 16.9% in 2020 AD. In electric bus, the primary power source is replaced by an electric motor, and the motorizing of powertrain system makes body structure changes along with the increased load on the vehicle battery. The battery weight would change the weight distribution of the vehicle, and cause the impact on handling and comfort during traveling. With CAE's technology, the vehicle dynamic simulation with the overall bus structure could more precisely predict the vehicle behavior during the different maneuver, and improve its handling and comfort.

This research investigated the electric bus stability with different steering inputs, and predicted the dynamic characteristics of the electric bus. The rigid body dynamic simulation model vehicle was established, and then the bus structure was replaced with the flexible body from structure analysis. Both simulation models would be analyzed. This study could present that the application of flexible

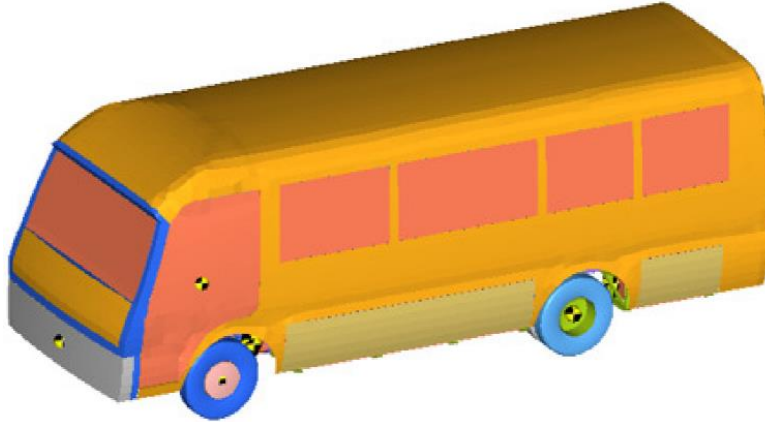
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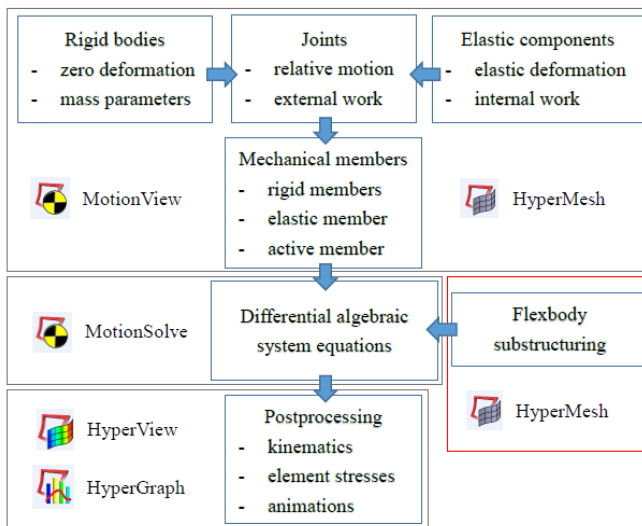
multi-body dynamics simulation based on actual body deformation could affect the behavior of vehicle handling simulation, and it could provide more precisely prediction.

## 2 Bus model

The bus CAD model was established with Hyperworks simulation software [1-3]. The model file was read into MotionView along with the sets of suspension systems, tires, steering group and connected components to complete the rigid motion model of electric bus body model, as shown in Figure 1. Later, the rigid bodies in the model were substituted by the flexible body of vehicle structure to build the flexible body dynamic model. Detailed modelling process was shown in Figure 2.

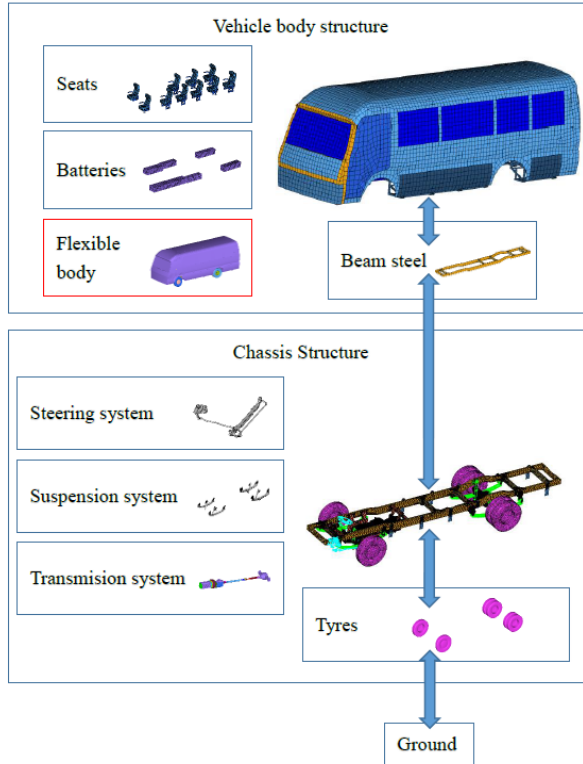


**Figure 1.** Vehicle model diagram.



**Figure 2.** Flowchart of flexible multibody dynamic analysis.

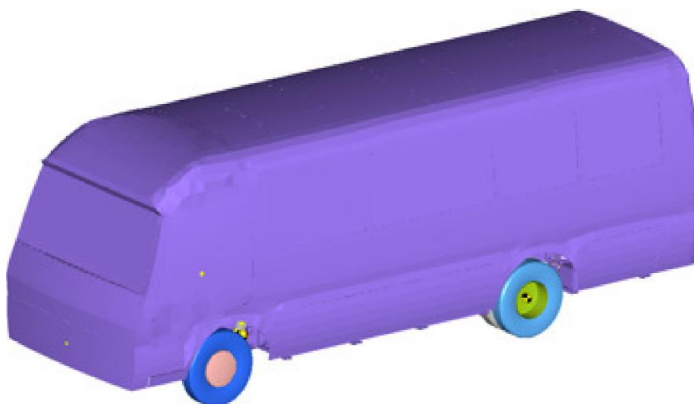
The vehicle model was divided into two major parts: the body structure and chassis structure. The body structure comprised bus body, battery, seat, beams. The chassis structure comprised steering systems, suspension systems, tires, transmission. The body structure was fixed on the top of the chassis structure. The flexible body would replace the rigid body, and it was marked within the red frame. The vehicle structure diagram was shown in Figure 3.



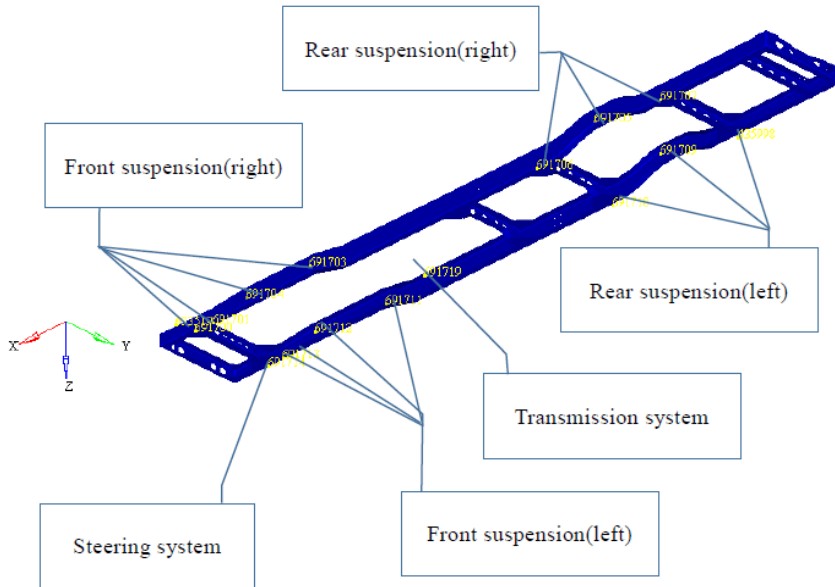
**Figure 3.** Vehicle structure diagram.

### 2.1 Vehicle flexible body structure

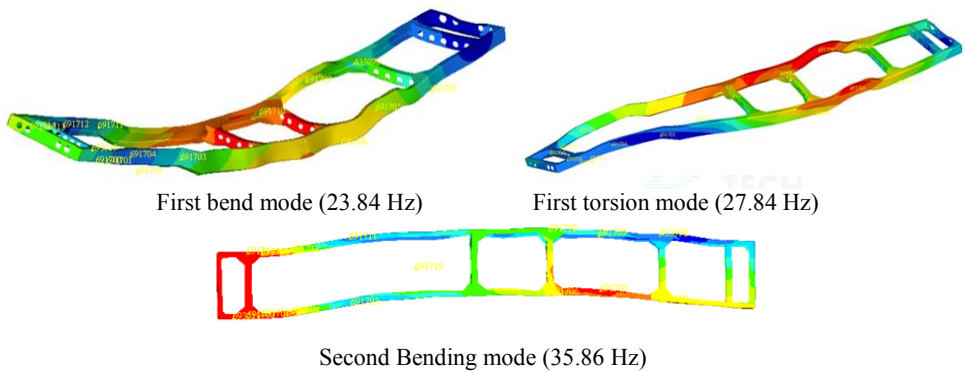
In this study, flexible body structures would replace the rigid body in vehicle dynamic model. The flexible bus body and flexible beams were shown in Figure 4 and Figure 5, respectively. The major selected modes of flexible body were torsional modes, and longitudinal and lateral bending modes. The first three mode shapes were shown in Figure 6. Since large vibration transmitted to the vehicle body is generally below 50 Hz [4]. The selected modal frequencies were up to 70 Hz, as shown in Table 1.



**Figure 4.** Bus flexible body.



**Figure 5.** Beam flexible body and binding locations.



**Figure 6.** First three mode shapes of beam.

## 2.2 Steering system

The vehicle steering system included a steering gearbox to turn the wheel spindles. All parts were considered as a rigid body. The system was shown in Figure 7.

## 2.3 Suspension system

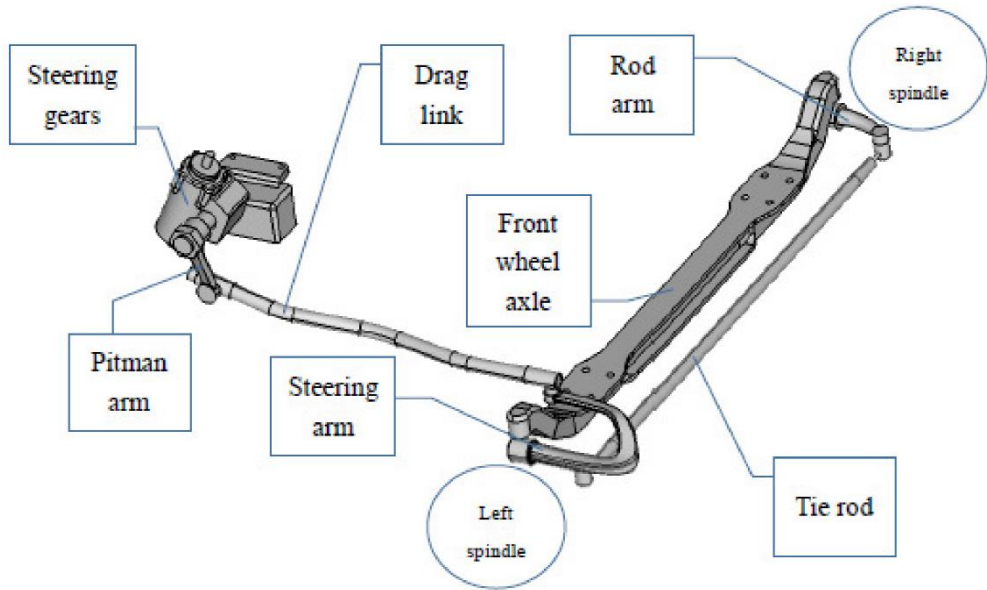
The vehicle suspension system of front and rear wheels were semi-elliptical leaf springs. Each suspension was equipped with four plates and a damper. A 10mm thickness of steel plate was on the top, and the other three were 8mm thick plates. The length of front suspension plates was 1247mm, and the center of plates was connected to the fixed contact of the front axle. The length of rear suspension plates was 1366mm, and the center fixed contact was connected to the differential. The gap between each piece was 5mm. Four damper tubes were installed in the vertical direction. The stability bar was attached to the bottom two front damper tubes, as shown in Figure 8.

## 2.4 Driveline system

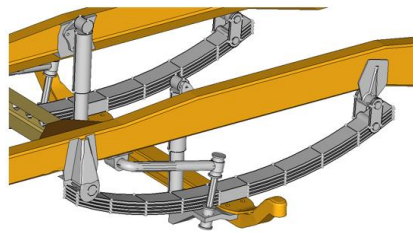
The driveline system included a 75 kW permanent magnet synchronous motor, clutch, six-speed manual gearbox, drive shaft, and differential [5], as shown in Figure 9.

**Table 1.** Flexible body modes.

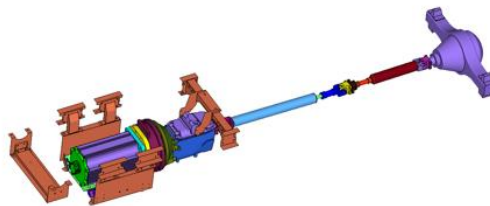
Flexible body modal frequency		
Order	Mode Frequency(hz)	Mode Type
7	18.258284	Longitudinal torsion(back fixed)
8	22.830112	Vertical bending(back fixed)
9	23.845562	1 <sup>st</sup> lateral bending
10	27.841775	1 <sup>st</sup> longitudinal torsion
11	30.379962	Lateral bending and longitudinal torsion
12	30.925637	Lateral bending and longitudinal torsion (2 fixed)
13	31.372244	Lateral bending and longitudinal torsion (middle fixed)
14	33.339106	Lateral bending(back fixed)
15	33.643737	Longitudinal bending(back fixed)
16	35.645866	Longitudinal bending and vertical bending(back fixed)
17	35.865369	1 <sup>st</sup> Vertical bending
18	37.269394	Vertical bending and lateral bending
19	37.590479	2 <sup>nd</sup> lateral bending
20	39.564707	Lateral bending(2 fixed)
21	40.209258	3 <sup>rd</sup> lateral bending
22	41.208339	Vertical and torsion(front right wheel)
23	41.733302	Vertical bending(front end)
24	42.706628	2 <sup>nd</sup> longitudinal torsion
25	43.900234	Longitudinal torsion (steering system)



**Figure 7.** Steering system configuration diagram.



**Figure 8.** Suspension system configuration diagram.



**Figure 9.** Suspension system configuration diagram.

### 3 Simulation and analysis

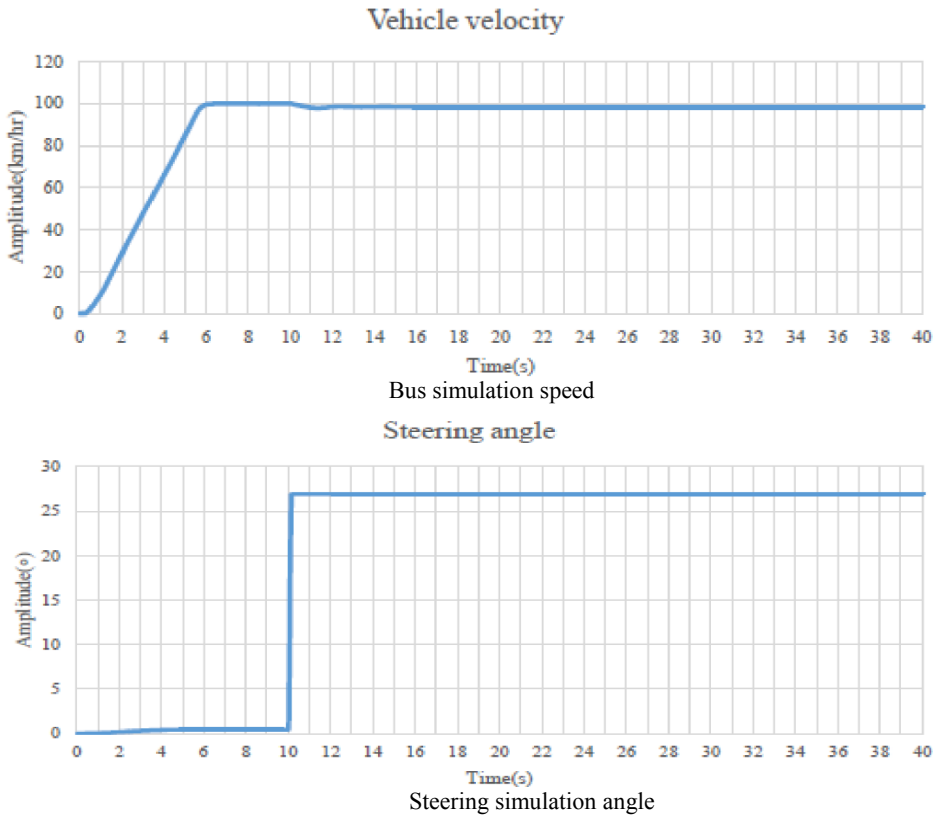
#### 3.1 Simulation conditions

This research referenced the ISO7401 regulation of the road vehicles transient open-loop response test method which was suitable for passenger cars and light trucks. The vehicle speed must reach 100 kilometers per hour, and the speed difference should not exceed 2 kilometers per hour. The yaw rate should be in steady state with the difference less than 0.5 degrees per second. The steering signal should increase from 10% to 90% within 0.15 seconds, and the throttle position should not change during the steering test. Tests were divided into the left turn and right turn, and the steering wheel angle was determined by the steady-state tests of constant radius circle [5].

The total simulation time was 40 seconds, and steering wheel angle rotated to 25.91 degrees from 10 and to 10.15 seconds, as shown in Figure 10. The left lateral acceleration would reach 400 meters per second after turning the steering. Simulation parameters are shown in Table 2.

**Table 2.** Steering turn parameters.

Parameters of Simulation	Value
Velocity $v_x$	100km/hr
Steady state lateral acceleration $a_y$	4m/s <sup>2</sup>
Correction steering wheel angle $\delta_{cor}$	0.42°
Steady state steering wheel angle $\delta_{h@ss}$	25.919°(L), 27.023°(R)



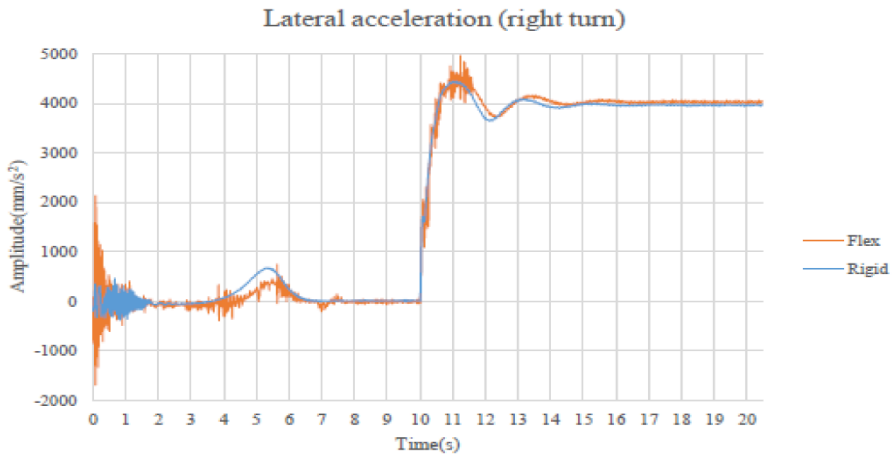
**Figure 10.** Vehicle speed and steering angle.

### 3.2 Simulation results and analysis

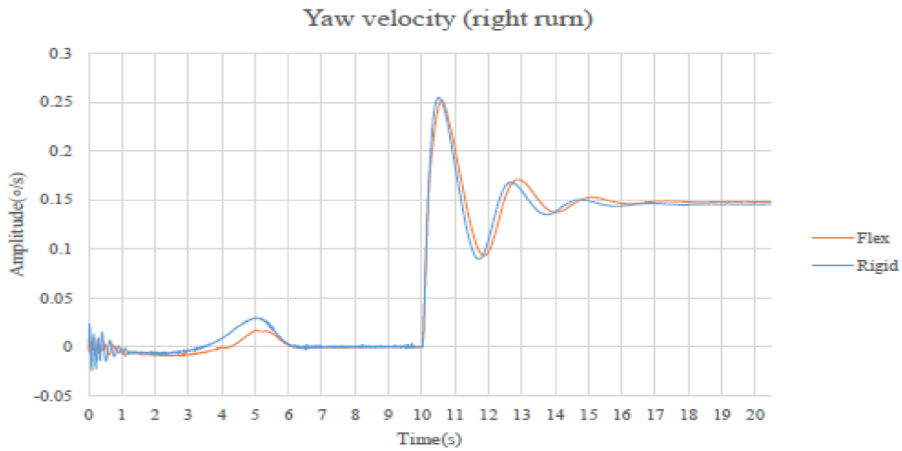
In this research, the steering step input simulations were analyzed. In addition to the comparison between left and right turns, the comparison between the rigid body and flexible body simulations was also included.

During the right turn, the lateral acceleration of rigid and flexible body simulation was shown in Figure 11. The flexible body simulation data reached the steady state later than the rigid body simulation, which represented the flexible body had a longer response time. The deformation of

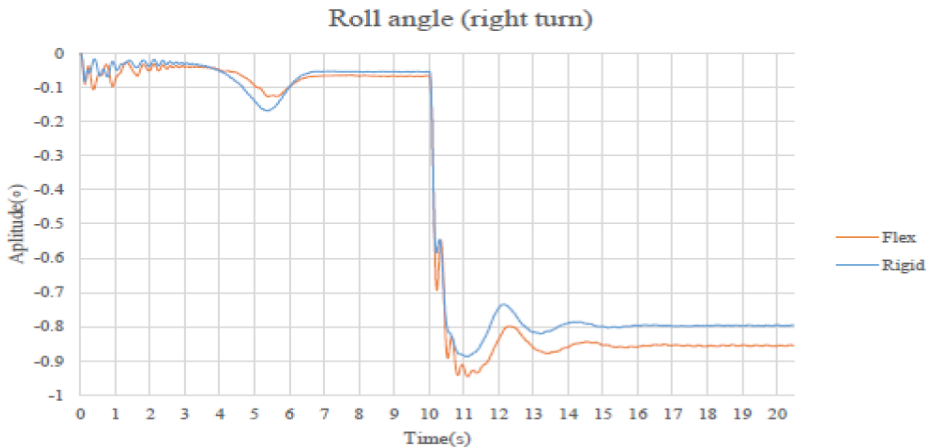
vehicle body structure caused vibration during the steering turn, so the time to reach the steady-state was delayed. Yaw rate response was shown in Figure 12. The flexible body simulation also showed a longer response time. Over time response of roll angle was shown in Figure 13. Since the flexible of bus structure, the flexible body simulation had longer response time and higher peak value.



**Figure 11.** Lateral acceleration during right turn.



**Figure 12.** Yaw velocity during right turn.



**Figure 13.** Roll angle during right turn.

For left turn simulation, the lateral acceleration, yaw velocity and roll angle response were presented in Figures 14, 15 and 16, respectively. Since the flexible body dynamic simulation allowed deformations of vehicle body, the response time to reach steady-state of flexible body simulation was longer than that of the rigid body dynamic simulation. The peak values of flexible body simulation were also higher than that of the rigid body simulation.

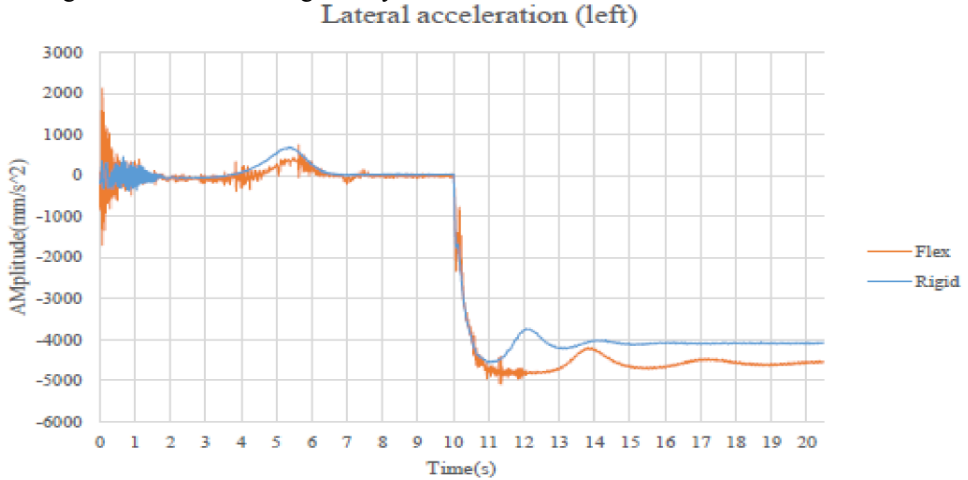


Figure 14. Lateral acceleration during left turn.

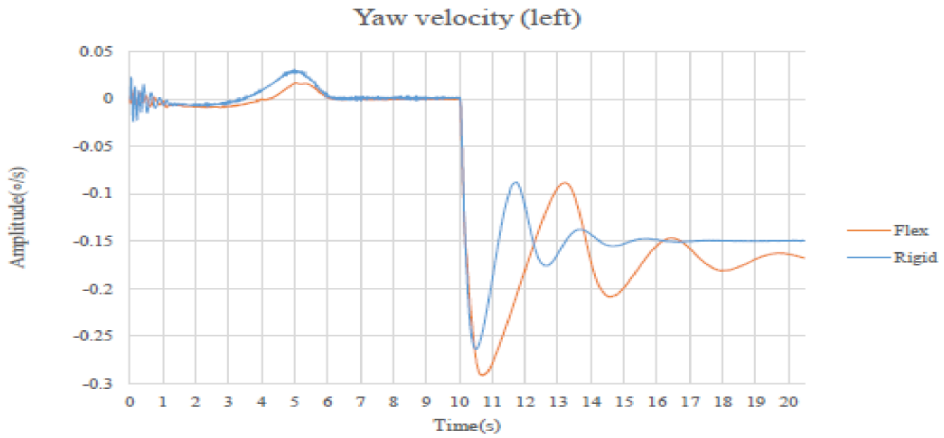


Figure 15. Yaw velocity during left turn.

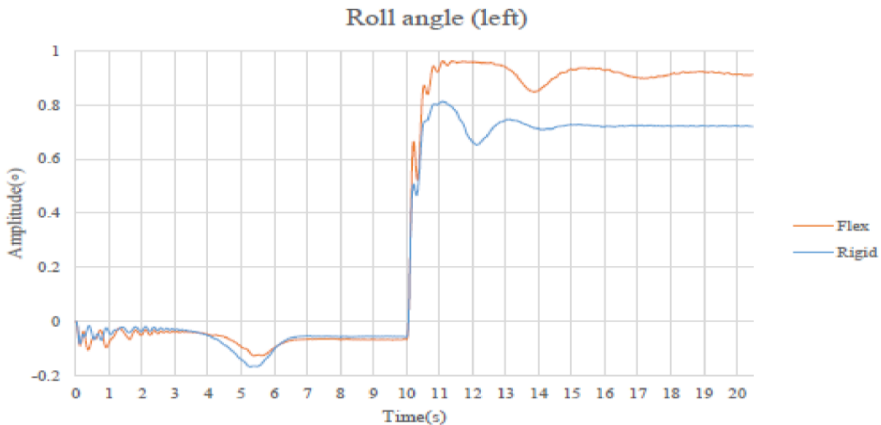


Figure 16. Roll angle during left turn.

The response time of flexible body simulation was longer, because the bus body was deformable which extended the vibration time. With the batteries and seats, the vehicle center of gravity shifted to the left, which caused the higher values of lateral acceleration, yaw velocity and roll angle during the left turn simulation. Table 3 presented the summary difference table of step steering input response between the flexible body and rigid body simulations.

**Table 3.** Summary table of step steering input response.

Percentage of data difference of Flexible body from rigid body	
Parameter	Percentage of data difference
Steady-state yaw velocity response gain	+7.14%
Lateral acceleration response time	+32.34%
Yaw velocity response time	+8.47%
Roll angle response time	+5.51%
Lateral acceleration peak response time	+15.51%
Yaw velocity peak response time	+33.06%
Roll angle peak response time	+13.43%
Overshoot value of lateral acceleration	-12.13%
Overshoot value of yaw velocity	-6.02%
Overshoot value of roll angle	-35.32%

## 4 Conclusions

This research presented dynamics simulations of electric bus, and replaced the rigid bodies with flexible bodies in multi-body dynamic model. According to the steering test regulations, dynamics simulations were performed and the results were presented. The conclusions were presented as below.

1. The elastic deformation of the body caused the vehicle vibration response times lengthen. Comparing with the rigid body model which did not have body flexibility, the flexible body model which represented the elastic deformation during steering turning simulation was closer to the actual performance of real vehicle.

2. The flexible vehicle parts could exhibit more detail motion and vibration, and this vibration would pass through vehicle structure.

3. The geometry of vehicle was not symmetric, which caused the higher normal load of right rear tire during the left turn simulation. This higher tire load would act on the vehicle body and caused higher body deformation. This was the reason that left turn had higher yaw velocity and roll angle. This behavior would not be predicted with the rigid body model. So, the flexible body simulation could provide more realistic data.

4. From the tire load data, the vehicle body's longitudinal torque was different between the left turn and the right turn. This would affect the steering performance. With the longer vehicle body, such as bus and truck, the flexible body model provided more accurate results of the simulation.

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