



Influence of Carbody Flexibility on Vertical Vibration Level of Rail Vehicle

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Abstract. Nowadays, modeling rail vehicles as a multibody in the dynamic simulation of ride comfort with a rigid carbody approach is less relevant—the analysis results are less accurate. The literature review shows that the first vertical bending mode vibration in the flexible carbody coincides with the human sensitivity range according to ISO 2631, in the frequency of 5 to 15 Hz. It can match the vibration from the bogie suspension due to the excitation of track irregularities. This study compares the vibration level in the rigid and flexible car body models when the vehicle travels through a straight track with irregularities. The flexible carbody is modeled using ANSYS software, then simulating the flexible vibration mode of the carbody and then imported to the UM software. The UM software will add components such as bogies, air springs, and traction rods. The results show differences in the vibration level for rigid and flexible carbody. On the flexible carbody model, higher-level vibrations appear in the 9 to 20 Hz frequency range due to the influence of the carbody first vertical bending mode vibration frequency of 13.76 Hz, which is not present in the rigid car body model. Thus, it can be concluded that modeling the carbody flexibility is highly recommended for analyzing the multibody dynamics simulation, especially for ride comfort analysis.

Keywords: Rail vehicle, ride comfort, rigid carbody, flexible carbody, vibration level.

1 INTRODUCTION

Passenger coaches as rail vehicles are designed with consideration of ride comfort. Passenger comfort can be influenced by several factors, including the vibration level that occurs in the carbody. Carbody vibrations can be generated from wheel-rail contact excitation transmitted from the bogie through the suspension system. The higher the speed of the vehicle travels, the higher the frequency that will be excited from the track [1, 2]. On the other hand, vehicles traveling at high speeds tend to have lightweight structures that make up the carbody. The lightweight carbody will produce a flexible vibration mode at low frequencies that can match the rail excitation vibrations received by the carbody [3]. The resonance potential coincides with the human sensitivity range according to ISO 2631. As shown in Fig. 1, human sensitivity to vertical vibrations ranges from 5 to 15 Hz [4].

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The potential for resonance can be avoided when designing the rail vehicle. In the rail vehicle design stage, vibration levels will be input in analyzing passenger comfort levels. Ride comfort analysis is included in the multibody dynamics analysis, carried out first through simulation before field testing. The frequency that coincides with the human sensitivity to vertical vibration range is flexible vibration mode frequency, namely the first vertical bending mode [5]. It makes the rigid carbody approach less relevant in multibody modeling because it ignores carbody flexibility effect on assessing the carbody vibration level. A rigid carbody only considers the rigid modes, which are bounce and pitch vibration modes. The flexible carbody approach will count the effects of flexible vibration modes, such as bending and torsion, that occur at low frequencies in analyzing vibration levels in the carbody [6, 7].

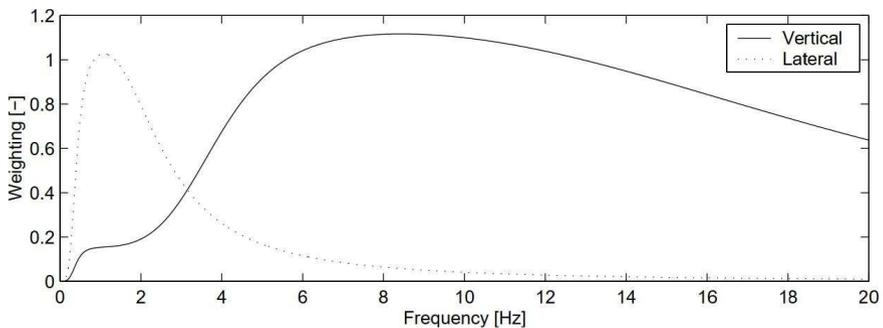


Fig. 1. Comfort weighting according to ISO 2631 [4]

Compared to the rigid body for the carbody, the flexible body model approach is important in the design stage of rail vehicles, especially in looking at the carbody vibration level. This study focuses on looking at the carbody vibration response through power spectral density by measuring the dynamic response in terms of carbody acceleration. The carbody is modeled as both a flexible and rigid body to see the differences. The influence of speed and track irregularity excitation are also observed to see the vibration responses that appear. The observed vibration levels focus only on the vertical direction.

2 VEHICLE MODELLING AND VALIDATION

The rail vehicle model refers to one type of passenger coach the domestic industry produces. The multibody model of the vehicle consists of two bogie subsystems and a carbody, which are connected by the secondary suspension system consisting of air springs and traction rods. Each bogie subsystem consists of a bogie frame and two wheelsets modeled as rigid bodies connected by the primary suspension. In this study, two models of carbody, i.e., the flexible and the rigid carbody, were examined. Integrated rigid and flexible bodies were modeled through Universal Mechanism multibody dynamic simulation software. The carbody was modeled as a flexible body using the finite element method in ANSYS software. Figure 2 shows a schematic diagram of the vehicle model.

Before integrating the flexible carbody with the rigid bogie, modal analysis was conducted using ANSYS software to obtain the flexible carbody mode. Figure 3 shows the corresponding flexible modes of the carbody model. The mode that is the focus of this study is the first vertical bending mode, which appears as the third mode. This mode is more easily excited by the track irregularities and coincides with the range of human sensitivity to vertical vibrations. The modes obtained were then compared with previous research to validate the results obtained. Table 1 compares the results of this flexible mode study and the previous studies. The frequency range of the first mode in the previous studies was 9.1 Hz to 10.9 Hz, with the first bending mode appearing in the 9.1 Hz to 11.125 Hz range. The first mode in this study is at 8.63 Hz, with the first bending mode at 13.76 Hz. This variation occurs because each carbody model has different stiffness and mass, as in this study. However, the values obtained are still within the range of human sensitivity to vibration, so it is interesting to see the effect on carbody vibrations.

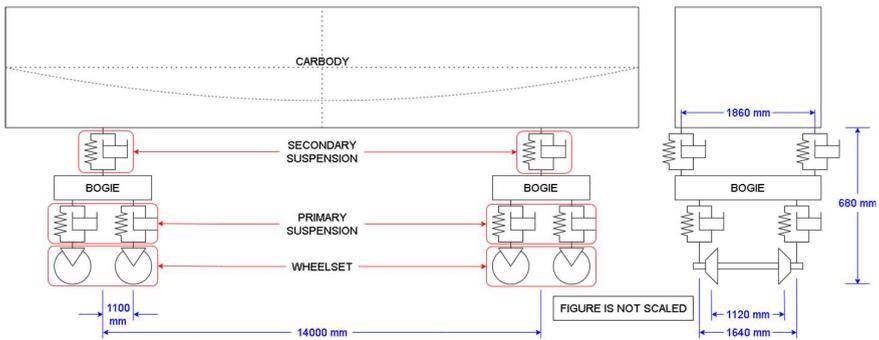


Fig. 2. Schematic diagram of rail vehicle.

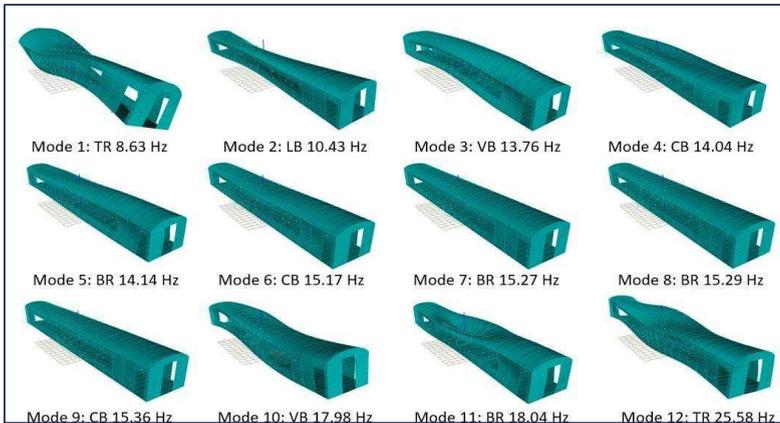
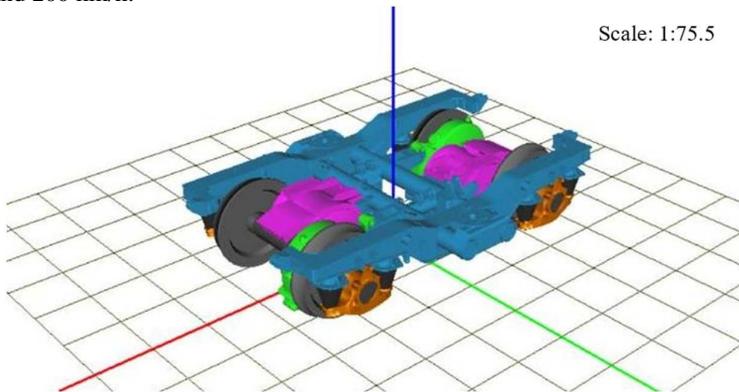


Fig. 3. Carbody flexible modes.

TABLE 1. Flexible mode comparison

Studies	First Flexible Mode (Hz)	First Bending Mode (Hz)
Orvnas, A. 2010 [8]	9.1	9.1
Li, Y. et al. 2016 [9]	10.03	10.03
Ling, L. et al. 2018 [10]	9.12	10.14
Wang, Q. et al. 2018 [11]	10.203	11.125
Sun, W. et al. 2016 [12]	9.15	9.15
Current study	8.63	13.76

The finite element method is also used to define the nodal interface. The nodal interface will be the locating point for attaching the secondary suspension, such as the air springs and traction rods, as the connection between the carbody and the bogie subsystem. The flexible carbody model is imported into the Universal Mechanism software to be integrated with the rigid bogie subsystem model shown in Fig. 4. The rigid-flexible vehicle model is simulated on a tangent track with the irregularities provided in the Universal Mechanism library, namely UIC Good and UIC Bad. The UIC Good irregularity has a lower deviation than the UIC Bad, as shown in Fig. 5 [13]. The model with a rigid carbody was also run to compare the vibration response with the flexible carbody model. The vehicle speed variations used in this study were 80, 120, and 200 km/h.

**Fig. 4.** Rigid bogie subsystem.

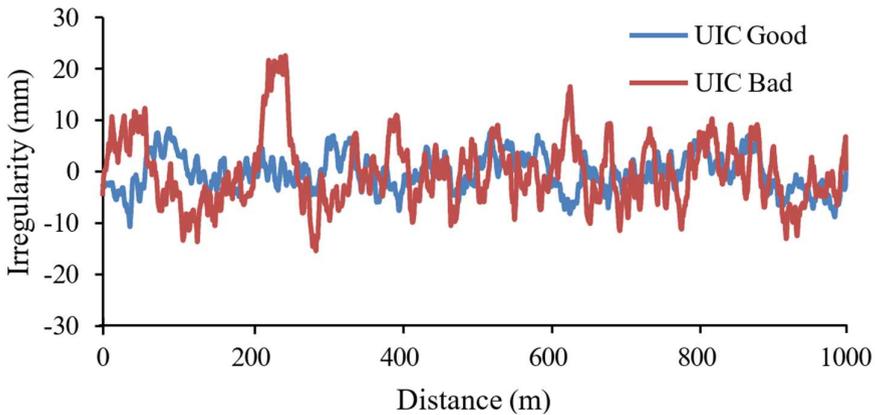


Fig. 5. Typical irregularity.

The equation of motion for the multibody system, which includes constraints like the vehicle and track system, is expressed through a series of differential and algebraic equations, as shown in Equation (1) [14].

$$\left. \begin{aligned} \mathbf{M}\ddot{\mathbf{q}} + \mathbf{C}_q^T \boldsymbol{\lambda} &= \mathbf{Q}_e + \mathbf{Q}_v \\ \mathbf{C}(\mathbf{q}, \mathbf{t}) &= \mathbf{0} \end{aligned} \right\} \quad (1)$$

\mathbf{M} is the system mass matrix, \mathbf{q} is the vector of the system generalized coordinates, \mathbf{C} is the vector of the system constraint, \mathbf{C}_q is the Jacobian matrix of the constraint equations, $\boldsymbol{\lambda}$ is the vector of the Lagrange multiplier, \mathbf{Q}_e is the vector of externally applied force, and \mathbf{Q}_v is the vector of inertia forces, which is quadratic to the velocity that arises from differentiating the kinetic energy to time and the system generalized coordinates. The equation includes the modal mass matrix, its associated modal stiffness matrix, and the elastic coordinates of the flexible body, i.e., the carbody. The external forces applied to the system bodies include the suspension and wheel-rail contact forces. The vector of system constraints describes the mechanical joints.

3 RESULTS

The effect of carbody modeling on vibration levels is seen in the frequency domain through power spectral density (PSD) acceleration in the vertical direction. Vertical acceleration is taken at the measurement point on the carbody, as shown in Fig. 6, namely on the carbody floor above the bogie and in the center of the carbody floor. The measurement location retrieval is according to Ling [10]. Collecting and processing of vertical acceleration data from the simulation results is carried out in multibody dynamic software.

Figure 7 shows the phenomenon in the flexible carbody when the vehicle model is run at 120 km/h on a track with UIC Good irregularity. Vibration increases at the first vertical bending frequency of around 13.76 Hz on the flexible carbody model. It can be seen from the vertical acceleration power in the graph, which is higher for the flexible

carbody than the rigid carbody at the three measurement points. For the rigid carbody, vibrations above the bogie are higher than at the carbody center. Meanwhile, in the flexible carbody, vibrations at the center of the carbody are higher than at the location above the bogie, as seen in Fig. 7(b). Resonance potential for the first vertical bending mode within the human sensitivity range cannot be detected in rigid carbody modeling. The model approach with a flexible carbody will look at the influence of vibrations in modes of 5 – 15 Hz.

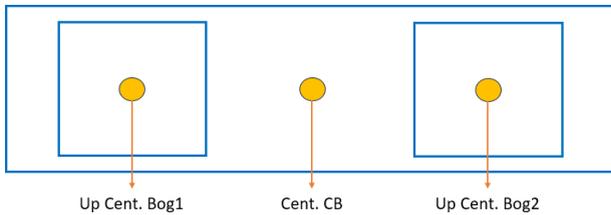


Fig. 6. Measurement points in carbody.

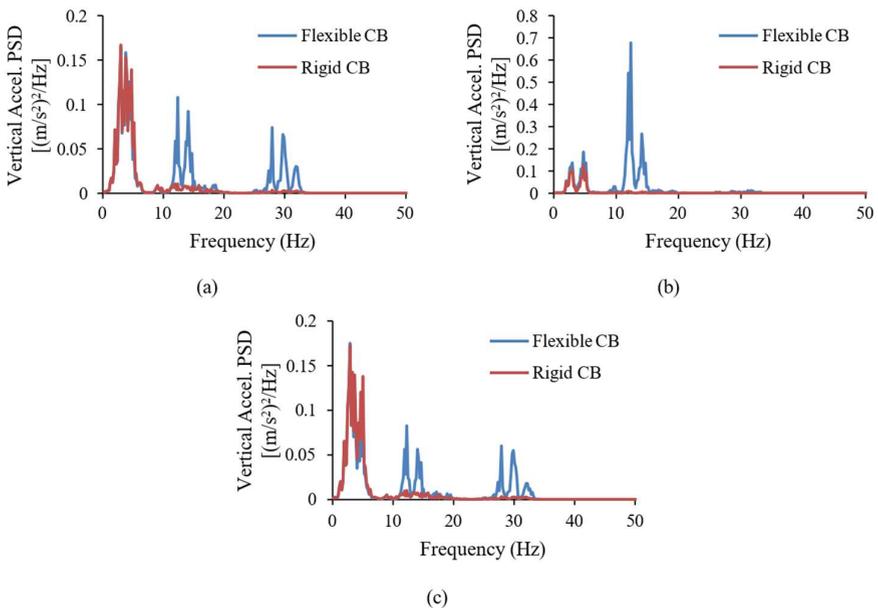


Fig. 7. Vertical acceleration of flexible and rigid carbody at 120 km/h: (a) Upper center of bogie 1, (b) Carbody center, and (c) Upper center of bogie 2.

Besides looking at the phenomena that arise based on the carbody model approach, the influence of speed variations for each vehicle model is also observed. The vibration response for the rigid carbody model can be seen in Fig. 8(a) – 8(c), while for the flexible carbody in Fig. 8(d) – 8(f). Both rigid carbody and flexible carbody show

similar vibration responses. The higher the speed, the higher the acceleration power that can be seen in the frequency domain. It can be caused by the higher the speed, the more increased the excitation frequency received by the vehicle from the track. However, an interesting phenomenon occurs in vehicle models with flexible carbody running at 120 and 200 km/h speeds. The carbody vibration response at the first vertical bending mode frequency at 200 km/h is much lower than at a speed of 120 km/h. It may occur because, at a speed of 200 km/h, resonance occurs in another flexible mode, which is not the focus of this study. Flexible mode vibration occurs at around 30 Hz for the location above the bogie and about 50 Hz in the middle of the carbody floor. These frequencies are outside the range of human sensitivity.

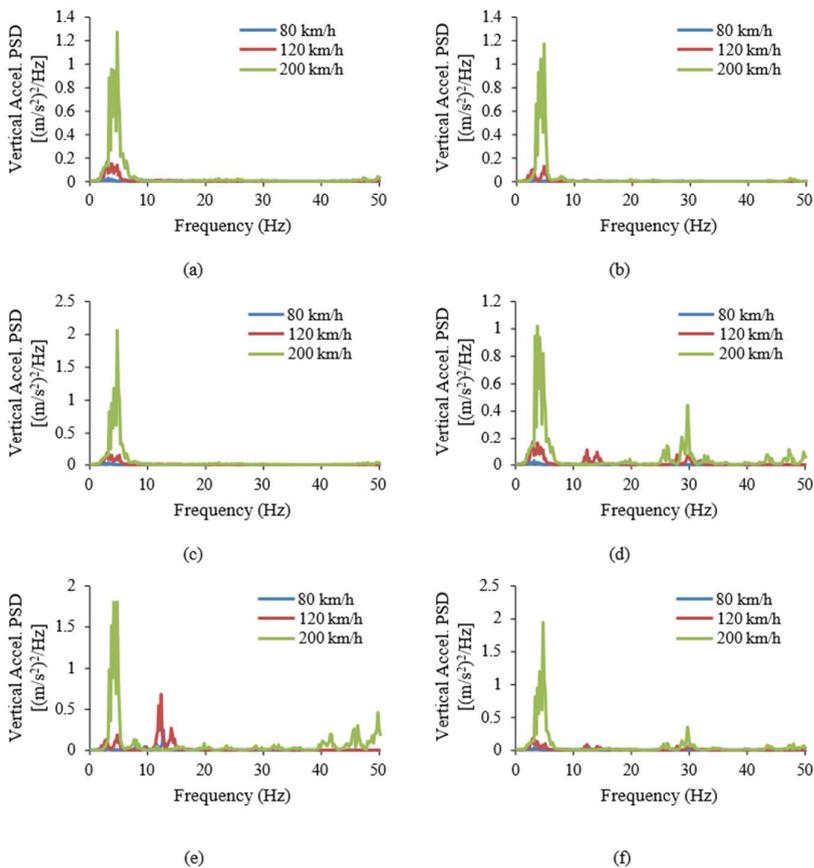


Fig. 8. Vertical acceleration at various speeds of: (a) Rigid carbody at upper center of bogie 1, (b) Rigid carbody at carbody center, (c) Rigid carbody at upper center of bogie 2, (d) Flexible carbody at upper center of bogie 1, (e) Flexible carbody at carbody center, and (f) Flexible carbody at upper center of bogie 2.

Track irregularity is one of the vibration-generating parameters. If the track irregularity is good, the vibrations due to the interaction between the wheels and the rail are relatively low, and vice versa. The vehicle is simulated at a 120 km/h speed on a track with UIC Good and UIC Bad irregularities. UIC Good is better than UIC Bad because it has a lower deviation. As shown in Fig. 9, vibrations on the vehicle when running on the UIC Bad track have higher power than when on the UIC Good track. The vibration response for the rigid carbody model can be seen in Fig. 9(a) – 9(c), while for the flexible carbody in Fig. 9(d) – 9(f). The rigid carbody and flexible models show relatively the same pattern; vibrations in the carbody increase on the UIC Bad track. However, as explained previously, a vibration response appears at the first vertical bending mode frequency on the flexible carbody model.

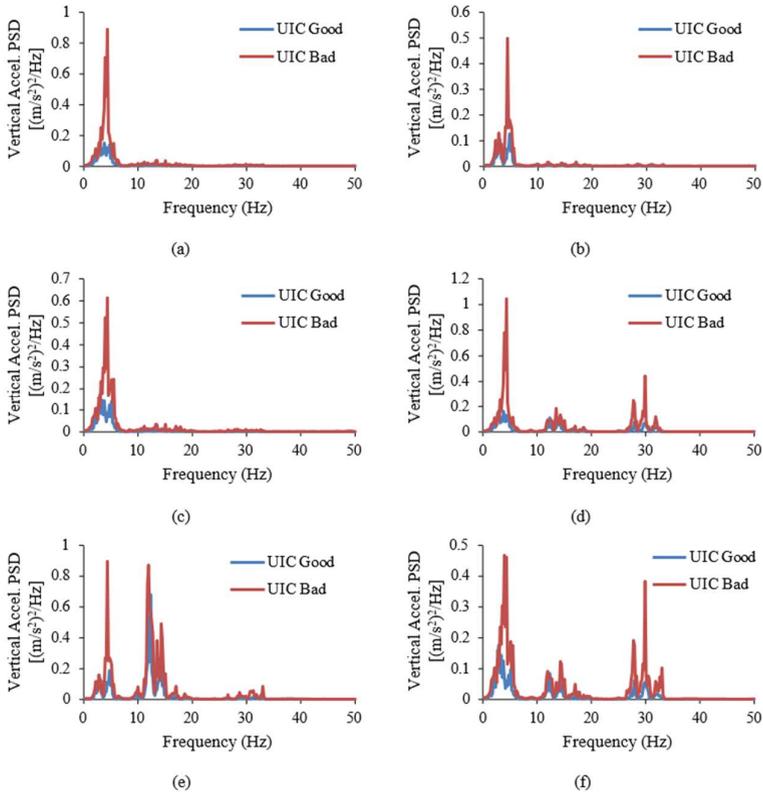


Fig. 9. Vertical acceleration at various track irregularities of: (a) Rigid carbody at upper center of bogie 1, (b) Rigid carbody at carbody center, (c) Rigid carbody at upper center of bogie 2, (d) Flexible carbody at upper center of bogie 1, (e) Flexible carbody at carbody center, and (f) Flexible carbody at upper center of bogie 2.

4 CONCLUSION

A multibody model of a passenger coach with a flexible carbody has been developed to compare with a rigid carbody model in the dynamic analysis of rail vehicles. From the comparison results of the two models, the influence of carbody flexibility on vibration levels for several variations in speed parameters and track irregularity can be observed when simulated with the input of the track excitation. A flexible carbody approach increases the level of vibration that occurs, especially in the middle of the carbody floor, in the frequency range of 9 Hz – 20 Hz, which coincides with the first vertical bending mode frequency of 13.76 Hz. Modeling a flexible carbody on a rail vehicle is the initial stage in analyzing passenger comfort. By knowing the vibration response in the carbody, alternative solutions to reduce the vibration amplitude can be sought and applied during the design process. The smaller the vibration amplitude felt by passengers, the more comfortable the vehicle will be for mass transportation.

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