ANALYSIS OF THE TRACTION WHEEL TORQUE OF THE STRADDLE MONORAIL NEGOTIATING A CURVED TRACK USING THE FINITE ELEMENT METHOD

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Abstract - Bogie is an important component in monorail train that determine the train curving radius and the load capacity. This paper analyses the traction wheel torque of a monorail train which passes through a curved track. A numerical analysis was performed using Simwise4D commercial software. Two new straddle-type of monorail bogie models were prepared for the simulations; namely, the UTM100 model, which is equipped with stabiliser wheels mounted between the two steering wheels, and the UTM125 model, which is equipped with stabiliser wheels mounted parallel to the steering wheels. The train and its trajectory were modelled as a multi-body system. The trajectory was modelled in a horizontal plane with various curve radiuses of 40 to 150 m. The range of motion speeds was selected as 20 to 60 km/h. The results indicate that the traction wheel torque obtained with the UTM125 bogie is generally smaller than that obtained with the UTM100 bogie. The torque differences were substantial when the train negotiated a track with a small radius of curvature, but they were smaller for a large radius. The resulting torque performance can be used as an initial consideration when selecting a monorail bogie model.

Keywords: Straddle monorail, Traction wheel torque, Curving performance.

1. Introduction

The role of efficient and effective transportation infrastructure is essential to support economic activities. Electric train transportation is more environmentally friendly and more energy-efficient when compared to other transportation such as road, sea, and air transportation systems. A study of infrastructure development when High-Speed Train (HST) transportation is operated to connect several provincial capital cities in particular region has been performed comprehensively [1, 2]. Meanwhile, the use of the rail transportation system in the provincial capital of Indonesia can reduce road load and congestion, which will affect economic growth effectively [3].

Straddle monorail is one of the urban rail transportations which is very attractive for mass transit transportation systems for medium to high capacity. The straddle monorail has some advantages, such as light and unobtrusive civil structure, relatively small curve capabilities, and fast project implementation. The straddle-type monorail track can also be constructed by the elevated track above public roads without disturbing road traffic [4, 5]. The most promising transportation system to reduce the congestion problem in Jakarta is the monorail train, especially the straddle type [6]. However, the monorail should be well-operated in Jakarta city, where the topography has already been established. Therefore, the monorail should accomplish the general requirement such as safety, reliability, and comfort, as well as several specific requirements, i.e., good turning ability shown as a turning radius of fewer than 60 m and turning velocity of 20 km/h; having gradient ability which is greater than 5 %; supporting load capacity of 24 tonnes; performing straight moving velocity of 70 km/h [7].

In order to realise the requirements, the new monorail train bogie, which can negotiate on a relatively low curving radius and have a high load capacity, has been prepared. We developed two new straddle-type bogies models, UTM100 and UTM125, as shown in Figure 1. These models have a specific structure with double traction wheel shafts that are closer than that in a common monorail bogie since this is intended to obtain high enough load capacity
and achieve the desired curving radius that can be negotiated. The UTM100 model has stabiliser wheels mounted between the two steering wheels, and the UTM125 model has stabiliser wheels mounted parallel to the steering wheels [7].

One of the most important technical performances when negotiating with a monorail train at a curved track is the torque value measured in the traction wheel. Therefore, the torque of the traction wheel of the monorail train when negotiating a curving trajectory was analysed numerically for two bogie models of UTM100 and UTM125. Based on understanding the performance of the monorail during the negotiation a curved track, therefore this can be used as an initial design consideration when selecting the type of monorail train bogie.

Generally, the dynamic performance of a railway vehicle concerning safety is evaluated in terms of specific performance indices, such as quantitative measurements of ride quality, vehicle stability, and vehicle curve-negotiation capability [8]. When negotiating a curving track, the wheels of a conventional railway vehicle are generally misaligned radially. This leads to increased lateral contact forces, wear, torque, and risk of derailment, among other issues. Relieving these problems can improve the curving performance of a railway vehicle.

Nagurka [9] researched the steady-state and dynamic curving performance of rail passenger vehicles. Wang et al. [10] reviewed research worked on the wheel-rail dynamic performance of railway curve negotiation focusing on the mechanism and calculation method of curve negotiation, analysis and assessment of the dynamic performance of the vehicle, vehicle parameters effects on the dynamic performance, and the influences of railway parameters on the dynamic performance. Field experiments can investigate parameters in curving performance, but they are complex and expensive. Therefore, some attempts have been made to examine curving parameters using a full-scale test stand [11, 12].

In particular, for monorail railways, the curving performance of monorail vehicles can be improved by using single-axe bogies, but they have relatively small load capacities. Hitachi has been developing several new designs of monorail bogies, including an articulated bogie model that can negotiate a sharp curve with a radius as low as 40 m [5]. Another technique to improve the curving performance of a monorail is applying a passive steerable bogie model [13-15].

2. Simulation

A series of simulation steps were performed, such as creating a CAD model of bogie components using Solidworks commercial software, assembling the models to create a virtual bogie prototype, and then performing the CAE analysis of the bogie prototype using Simwise4D commercial software.

2.1 Monorail Train

The monorail train consists of a car body installed of two bogies. The bogie is composed of a suspension system, travelling wheels, steering wheels, stabilising wheels and a braking system. Travelling wheels provide traction and support for most vertical loads. Stabilising wheels are to maintain train balance and prevent vehicle roll. Steering wheels guide the train's direction, especially when negotiating a curved track. The suspension system consists of coil springs, shock absorbers, a pin bolster, and a suspension linkage mechanism. The brief anatomy of the bogie system is shown in Figure 1. The dynamic multi-body model of a straddle monorail train can be shown in Figure 2.
A full-scale CAD model of the bogie components was made using Solidworks commercial software. The models were assembled to create a bogie model. Then the two bogie models were assembled with a car body train to create a monorail train model. Then the monorail train model was used to perform CAE analysis with the commercial software of Simwise4D, which was modelled as a multi-body system. A series of simulations were conducted on the monorail train model assembled by the two-bogie of UTM100 and two bogies of the UTM125 model, respectively. The Simwise4D is an appropriate tool to calculate the dynamic response of a full-scale monorail train model.

Recent studies have also used multi-body dynamics simulation to the dynamic response of a monorail train straddle type moving on its trajectory [16-23]. Figure 2 shows the dynamic model of a double-axle non-steerable type of monorail bogie and its trajectory.

As shown in Figure 2, the monorail train’s car body is assumed to be rigid. The dynamic behaviour of a monorail train is assumed to be a discrete rigid multi-body system, where m is the mass, k is the spring constant, and C is the damping coefficient. The bogie frame is also assumed as a rigid body.

The basic equation of motion for the dynamic model of straddle type monorail train is based on Lagrange’s equation of motion as shown in Eq. (1), which has been widely used in other studies for dynamic models of monorail trains [16-27]:

\[
\frac{\partial}{\partial t} \left( \frac{\partial T}{\partial \dot{q}_i} \right) - \frac{\partial U_e}{\partial q} + \frac{\partial U_d}{\partial \dot{q}_i} + \frac{\partial D}{\partial q} = 0
\]

Where \( T \) is the kinetic energy, \( U_e \) is the potential energy, \( U_d \) is the dissipation energy resulting from the damping of the system, and \( \dot{q}_i \) is a generalised coordinate.

The simulations were performed at several certain moving speeds of 20 to 60 km/h at increments of 10 km/h. The trajectories have various curve radii of 40 to 150 m at increments of 10 m. These moving velocities are commonly used in operating monorail trains [28]. The train was modelled using one driving motor placed at the front traction wheel axle of the front bogie, even though in real conditions, the driving motors would be mounted on each traction wheel axle. This was performed because of the limitations of the simulation process. The simulation data are presented in Table 1.

![Figure 2(a): The dynamic model of a monorail train using the UTM100 bogie](image)

![Figure 2(b): The dynamic model of a monorail train using a UTM125 bogie](image)

The spring constants of the suspension system were obtained from laboratory testing conducted according to JIS B2704 standards [29]. The trajectory model was modelled as a horizontal plane-curving track with a particular radius, as indicated in Figure 3.

![Figure 3: Simulation of monorail train showing train trajectory and its particular steps](image)
2.2 Trajectory Model

The track was modelled as a flat surface without any surface irregularity; hence dynamic response due to the irregular surface was neglected. The track is also considered as a rigid body without any deformation, so the effect of variation in the vertical load of the stiffness travelling wheel was neglected.

2.3 Tire Wheel Model

Ko and Song [30] used nonlinear vehicle models with a nonlinear tire model to estimate the stability region and simulate the dynamic behaviour of a vehicle. In this study, all tires were modelled as solid rubber-type models. The slip model between the surface of the wheel and the track is neglected.

3. Results

The original torque history data resulting from the simulation are indicated as stochastic data, so they should be filtered. Figure 4 shows the filtered simulation data of the UTM100 and UTM125 models negotiating a curved track with a curving radius of 40 m and a moving velocity of 20 km/h.

As shown in Figure 3, there are categorised by five steps of the motion path. The first step is forward motion in the x-axis direction, i.e., from O to A, in which all wheels are still on the straight track. The second step is the approaching transition motion, i.e., from A to B, where the front wheels are on the curving track. However, the rear wheels are still on the straight track. The third step is full curving motion, i.e., from B to C, where all wheels are completely on the curving track. The fourth step is the exit transition motion, i.e., from C to D, where the front wheels have already moved off the curving track onto the straight track. However, the rear wheels are still on the curving track. The fifth step is the exit straight forward motion along the y-axis, i.e., from D to E, where all wheels are completely on a straight track.

The first step occurs at \( t = 0 \) s and \( x = 0 \) m, as shown in Figure 4. The traction wheel torque is very high, about 16 kNm for both bogie models. This is attributed to the initial torque response to overcome the inertia of the train body. Subsequently, the torque significantly decreased to around one kNm for UTM100 and 2 kNm for UTM125 at \( t = 10 \) s and \( x = 45 \) m. The torque remained steady until \( t = 38 \) s and \( x = 190 \) m (point A).

In the second step, where \( t = 38 \) s to 43 s (point B), the traction wheel torque increased from 1 to 6 kNm for the UTM100 bogie model and from 2 to 4 kNm for the UTM125 bogie model. In the third step, i.e., \( t = 43 \) s to 48 s (point C), the traction wheel torque was relatively constant, around six kNm for UTM100 and four kNm for UTM125. In the fourth step, i.e., \( t = 48 \) s to 53 s (point D), the traction wheel torque decreased significantly from 6 to 1 kNm for UTM100 and from 4 to 2 kNm for UTM125. In the fifth step, i.e., \( t = 53 \) s to 70 s (point E), the traction wheel torque was relatively constant, around one kNm for UTM100 and two kNm for UTM125. This indicated that the torque condition at straight-forward moving before the curving track is very similar to that after.

Figure 4: Traction wheel torque of UTM100 and UTM125 bogies for a curve radius of R = 40 m and V = 20 km/h

Figure 5 shows the normalised torque graphs of monorail train models mounted by the UTM100 and UTM125 bogies. TS is the traction wheel torque of the monorail train while negotiating the straight track, and TC is that on a curved track. The simulations were performed for several curving radiiuses of tracks and moving speeds of 20, 30, 40, 50 and 60 km/h.

Figure 5a shows the simulation results for a moving speed of 20 km/h. At a curving radius of 40 m, the torque for the UTM125 bogie model is about twice that on straight track, while for the UTM100 bogie model, it was about 3.25 times the straight-track result. This indicates that a large enough torque is required to negotiate a small curving radius. When the monorail train negotiated a curving radius of 120 m, TC/TS for UTM100 and UTM125 was almost ununified with little differences. Therefore, it could be said that both models have nearly the same torque.

Figure 5b describes the simulation results for a moving speed of 30 km/h. At curving radiiuses of 40 m and 50 m, the traction wheel torque for the UTM100 model was not obtained because of locked conditions during the simulation. However, for the UTM125 bogie model, the simulations were performed successfully for every track curve. Generally, the traction wheel torque of the UTM125 model was slightly smaller than that of the UTM100 model.
Figure 5c indicates the simulation results for a moving speed of 40 km/h. At a curving radius of 60 m, the traction wheel torque for the UTM100 model was not acquired because of the locked condition during the simulation process. Locked conditions also occurred at curving radii less than 60 m. Therefore, the simulation was not performed with those conditions. The simulations for the UTM125 bogie model were performed successfully for every track curving radius. Commonly, the traction wheel torque value of the UTM125 model was also slightly smaller than that of the UTM100 model.

Figure 5d illustrates the simulation results for a moving speed of 50 km/h. At a curving radius of 70 m, the traction wheel torque of the UTM100 bogie model was not obtained because of a derailment incident during the simulation process. Therefore, the simulation was not performed for smaller curving radii at this moving speed.

Figure 5e explains the simulation results for a moving speed of 60 km/h. A derailment incident occurred with the UTM100 model at a radius of 80 m. Therefore, the simulations were again not performed for small radii. Unfortunately, a derailment also occurred for the UTM125 bogie model with radii of 40 m and 50 m. With a curve radius of 120 m, there was a trend for all graphs of TC/TS to become a horizontal line for every speed.

This exhibits that there is no substantial difference between torque value when a monorail train is negotiating a curved track with a curving radius above 120 m and that on a straight track.

Figure 5: Normalised torque (TC/TS) for several radii of a curving track and moving speeds of 20, 30, 40, 50, and 60 km/h

4. Discussion

As shown in Figure 4, the traction wheel torque increased when negotiating on a curved track due to the increased rolling resistance of all bogie wheels. Figure 6 shows a free-body diagram of the bogie wheels and the trajectory when negotiating a curving track.
When negotiating a curving track, the motion of the traction wheels changes to predominantly sliding motion in the lateral direction in addition to rolling and sliding motion in the longitudinal direction. This results in greater friction forces, as shown in Figure 7. The blue line indicates the friction force in the lateral direction is about 4000 N, and the red line indicates the friction force in the longitudinal direction is about 6000 N. Negative values in the figure indicate an opposite direction of the forces.

A similar effect also occurred when the bogie negotiated the curving track due to the change in motion of all the bogie wheels, i.e., traction, stabilising, and steering wheels. When negotiating the curving track, the rolling resistance increases, which affects the torque on the traction wheels. Therefore, the longitudinal and lateral friction forces at the traction wheels increased significantly to about 6000 N and 4000 N, respectively, as shown by the red line in Figure 7.

Similar studies to improve the curving performance of railway vehicles have been performed. The study of improving the curving performance of the straddle type of monorail train by using semi-active magnetorheological (MR) dampers has been carried out [32]. The study focused on the dynamic behavior of straddle-type monorail composed of multiple car body compared to that of single car body was performed [26]. A new method to improve the passing performance of...
monorail train negotiating a curving track by adjusting the track width was carried out [33]. The analytical study focused on a straddle-type monorail bogie mounted by an auxiliary steering device was performed [34].

In this study, due to practical use consideration, the effect of stabilizing wheel location of two bogie models indicated at UTM-100 and UTM-125 were analyzed using finite element method of Simwise4D commercial software. Based on the result of this analysis, future research will be focused on the development of new bogie model according to several technical considerations, i.e., modification of bogie structure, application of active or semi-active control for stabilizing, steering wheels, as well as suspension systems.

5. Conclusions

This study numerically analysed the traction wheel torque for a monorail train when negotiating a curving track. The important conclusions could be summarised as follows:

- During the full curving motion step, the value of the traction wheel torque of the UTM125 bogie model was smaller than that of the UTM100 model for the same speed.
- The torque differences for both bogies were relatively large when negotiating a small curve radius, but they became small when negotiating a large curve radius.
- Generally, traction wheel torques were inversely proportional to the curve radius.
- The traction wheel torque is directly proportional to the motion speed.
- The behaviour of the traction wheel torque when negotiating a curving track was shown on the normalised torque graphs (TC/TS). The results can be used as a preliminary consideration when selecting a bogie model based on the track's curve radius.
- At relatively low speeds, i.e., about 30 and 40 km/h, the UTM100 bogie model simulation was unsuccessfully completed when the curving radius was relatively small, i.e., 40 to 60 m, because of the occurrence of locking motion. The UTM125 simulations were also unsuccessfully finished when negotiating small curve radiuses, i.e., 40 to 50 m, due to derailment incidence at high speed of 60 km/h.
- Based on the simulation result, it could be used as initial consideration when developing the new bogie for the specific use of the monorail train.

Acknowledgements

The authors acknowledge the Directorate of Research and Community Service-University of Indonesia (DRPM-UI), Ministry of Research and Technology and Higher Education (RISTEKDIKTI), Republic of Indonesia, for funding this research in RAPID scheme. The authors also acknowledge PT MBW for technical support related to Solidworks commercial software and technical data.

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