Railway bogie vibration analysis by mathematical simulation model and a scaled four-wheel railway bogie set

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Abstract. The bogie is the part that connects and transfers all the load from the vehicle body onto the railway track; interestingly the interaction between wheels and rails is the critical point for derailment of the rail vehicles. However, observing or experimenting with real bogies on rail vehicles is impossible due to the operational rules and safety concerns. Therefore, this research aimed to develop a vibration analysis set for a four-wheel railway bogie by constructing a four-wheel bogie with scale of 1:4.5. The bogie structures, including wheels and axles, were made from an aluminium alloy, equipped with springs and dampers. The bogie was driven by an electric motor using 4 round wheels instead of 2 straight rails, with linear velocity between 0 to 11.22 m/s. The data collected from the vibration analysis set was compared to the mathematical simulation model to investigate the vibration behavior of the bogie, especially the hunting motion. The results showed that vibration behavior from a scaled four-wheel railway bogie set significantly agreed with the mathematical simulation model in terms of displacement and hunting frequency. The critical speed of the wheelset was found by executing the mathematical simulation model at 13 m/s.

1. Introduction

Hunting motion is a self-oscillation running off the centreline or a swaying motion of the railway vehicles while running on the railway track. This hunting motion is one of the general vibration behaviors of railway vehicles that always occurs; it affects riding comfort of passengers; it is a cause of wheel and rail damage; and, most seriously, it could cause the derailment of railway vehicles [1]. In order to minimize or eliminate the problem of hunting motion, the design of wheel and rail geometry needs to be corrected [2, 3], using suitable primary and lateral suspension stiffness and damping parameters, such as a special camping design and characteristics, nonlinear spring and damper coefficients [4-7], and take into consideration the relevant factors that affect the rail vehicles’ stability, and increase the critical speed [8-10] which results in riding comfort and safety.

This work was to investigate the relevant factors that affect the vibration behavior of railway vehicles, especially the hunting motion behavior. Two types of investigation tools were therefore developed, one being a mathematical simulation model, and the other was a scaled four-wheel bogie set. Then the vibration behavior and influence of the bogie’s parameters was investigated by varying the variables in
a mathematical simulation model, and the experimental result from the scaled four-wheel bogie set were compared with each other to authenticate the simulation results.

2. Methodology
In this research, as mentioned above, two types of investigation tools were developed. The mathematical simulation model was developed based on an existing theory for the dynamics of railway vehicle systems [1]. A scaled four-wheel railway bogie set was constructed in small scale, based on real railway bogie frame and dimensions.

2.1. Mathematical Simulation Model

Figure 1 shows the physical model of the bogie with independently rotating wheelsets. In this investigation model, the focusing point is the hunting motion stability. The governing differential equations of the motion of the bogie are given as [7]

\[
m_w \ddot{y} + \left( \frac{2 f_{11}}{v} + \frac{2 f_{11} r_0 \lambda}{a} \right) \ddot{\dot{y}} - 2 f_{11} \dot{\phi} + 2 f_{12} \dot{y} + W_0 \frac{\lambda}{a} y + F_{\text{sywi}} = 0 \tag{1}
\]

\[
I_{wz} \ddot{\psi} + I_{wy} \frac{\vartheta}{r_0 a} \ddot{\psi} + \frac{2 a f_{33} \vartheta}{r_0} \ddot{\phi} - \frac{2 f_{12}}{v} \ddot{\psi} - \frac{2 f_{12} \lambda}{v} \dot{\phi} + 2 f_{12} \psi + \frac{2 a^2 f_{33}}{v} \psi - a W_0 \lambda \psi + 2 f_{33} \psi = 0 \tag{2}
\]

where \( F_{\text{sywi}} \) is the suspension force, given as below [2]
where \( f_{33}, f_{11}, f_{12}, f_{22} \) are the nonlinear creep forces according to Kalker’s linear creep theory, the creep coefficients are given by [9]

\[
f_{33} = Gmn \left[ \frac{3\pi(1-\sigma^2)}{2E(A+B)} \right] \left( \frac{m^2}{3} \right) C_{11} \tag{4}
\]

\[
f_{11} = Gmn \left[ \frac{3\pi(1-\sigma^2)}{2E(A+B)} \right] \left( \frac{n^2}{3} \right) C_{22} \tag{5}
\]

\[
f_{12} = Gmn \left[ \frac{3\pi(1-\sigma^2)}{2E(A+B)} \right] \left( \frac{2}{3} \right) C_{23} \tag{6}
\]

\[
f_{22} = Gmn \left[ \frac{3\pi(1-\sigma^2)}{2E(A+B)} \right] \left( \frac{4}{3} \right) C_{33} \tag{7}
\]

\[
(A + B) = \frac{1}{2} \left( \frac{1}{R_w} + \frac{1}{r_r} + \frac{1}{r_w} \right) \tag{8}
\]

where \( R_w, r_w, r_r, G, C_\mu, \sigma, m, n \) are the wheelset rolling radius, transverse radius of wheel profile, transverse radius of rail profile, the shear modulus, non-dimensional Kalker coefficient, Poisson ratio and coefficients related to \( A \) and \( B \), respectively. And \( N \) is the wheel/rail normal force that is affected by the aerodynamic loads and motion of the vehicle. For this work, the important variables used in the mathematical simulation model such as creep force and several other parameters are shown in table 1. These were taken by measuring from the scaled four-wheel railway bogie set that was constructed for this work. In the simulations, the bogie speed was at 6.70 m/s, 8.96 m/s, and 11.22 m/s.

### 2.2. The Scaled Four-Wheel Bogie Set

One of the original tasks performed in this research was a scaled four-wheel railway bogie set. It was constructed in a small scale based on the real railway bogie frame configuration and dimensions with a scale of about 1:4.5 (see figure 2). The overall size of the scaled bogie is approximately 70 cm long, 55 cm wide, and 25 cm high; the driven wheels are not included in these dimensions. The bogie does not have power to run itself, it is therefore driven by the drive wheels that also support the bogie, instead of a straight rail track. Each drive wheel is supported directly to a driven wheel (train’s wheel). Therefore, one set of a scaled four-wheel railway bogie is composed of four drive wheels, and all wheels run at the same rotation speed controlled by an electric motor with a variable speed drive control system. In the experiment, the bogie operated from 0 – 11.22 m/s in terms of linear velocity by controlling the VSD control panel. See figure 3.
### Table 1. Parameters used in the mathematical simulation model

| Parameters                                      | Variable | Value       |
|-------------------------------------------------|----------|-------------|
| Wheelset mass                                   | $m_w$    | 11.6 kg     |
| Roll moment of the inertia of the wheelset      | $I_{wx}$ | 60.12 kg·m² |
| Spin moment of the inertia of the wheelset      | $I_{wy}$ | 0.92 kg·m²  |
| Yaw moment of the inertia of the wheelset       | $I_{wz}$ | 60.12 kg·m² |
| Wheel radius                                    | $r_0$    | 0.10 m      |
| Half of the distance between contact points on two rails | $a$     | 0.17 m      |
| Lateral creep force coefficient                  | $f_{11}$ | 2,589,438.65 N |
| Lateral/spin creep force coefficient            | $f_{12}$ | 1,006.63 N·m |
| Spin creep force coefficient                    | $f_{22}$ | 1.10 N·m²   |
| Longitudinal creep force coefficient            | $f_{33}$ | 2,750,559.28 N |
| Spring stiffness of lateral primary suspension  | $k_p$    | 400,000 N/m |
| Viscous damping constant of lateral primary suspension | $c_p$ | 1,800 Ns/m |
| Wheel conicity                                  | $\lambda$ | 0.05        |
| Weight of bogie                                 | $W_a$    | 245.25 N    |

![Figure 2. Main components and configuration of the scaled four-wheel railway bogie set.](image)
Figure 3. A scaled four-wheel railway bogie set on a stand and control panel.

In order to observe the bogie motion, for this first phase of the research, we focused on the hunting motion, so the important required data was the oscillation of the wheelset in terms of time-distance domain. Therefore, Arduino UNO board and HC-SR04 distance sensor were installed to collect the required vibration data, as shown in figure 4.

Figure 4. Displacement sensor installation position.

3. Results and Discussions

3.1. Validation of Mathematical Simulation Model

In order to investigate the vibration behavior of the railway bogie by using a mathematical simulation model, it was very important to validate the numerical simulation model before analyzing further steps later. In this work we compared the numerical simulation result with the reference model developed by
others [2] for ensuring that the developed numerical simulation model was correct. It was shown that both results were in agreement with each other, as shown in figure 5.

![Image](image_url)

**Figure 5.** Transversal displacement of the wheelset at the same parameters, between the developed simulation model and the reference model.

### 3.2. Simulation Results

![Image](image_url)

**Figure 6.** Transversal displacement of the wheelset while running at 11.22 m/s which is the maximum speed of a scaled four-wheel railway bogie set.
Figure 7. Transversal displacement of the wheelset while running at 13 m/s, which is where the critical speed appeared.

From the simulation results at lower speed, for example at 11.2 2 m/s (with the displacement-time relationship shown in figure 6), it was found that the displacement was continuously decreasing. This meant that the wheelset was still stable. However, in the simulation at 13 m/s it was found that the displacement was increasing. Therefore, it can be debated that 13 m/s is the critical speed where the wheelset loses stability to run on the track. Please note that, these simulation results were based on the parameter values shown in table 1, which are smaller than real railway bogie parameters, e.g. the wheel diameter. Therefore, the linear velocity of the wheelset found in this simulation is too low when compared to a real situation. In the real situation, this critical speed will cause the rail vehicle to be derailed. However, we also compared the results of the experiment that was performed with the scaled four-wheel railway bogie set, the results are shown in the following sections.

3.3. Experimental and Simulation Results
For the experiment with the scaled four-wheel railway bogie set, the instrument could vary the speed from 0 m/s to the maximum of 11.22 m/s. But, at low speed or velocity, the oscillation or hunting motion of the wheelset is also very low, and increasing when the speed was increased. Therefore, this experiment was performed at 6.70 m/s, 8.96 m/s, and 11.22 m/s, which is the maximum speed that this scaled four-wheel railway bogie can be operated at. After that, the experiment results were put together with the simulation results. A comparison of the results is shown in figures 8-10:
Figure 8. Transversal displacement of the wheelset while running at 6.70 m/s, comparison between experiment and simulation.

Figure 9. Transversal displacement of the wheelset while running at 8.96 m/s, comparison between experiment and simulation.
Figure 10. Transversal displacement of the wheelset while running at 11.22 m/s, comparison between experiment and simulation.

From the comparison results between the experiment and mathematical simulation model, when compared to each other at the same velocity, of course, the experiment and the simulation results are not perfectly aligned. However, the tendency of the curves is consistent and there are points that are comparable, see figures 8-10.

Firstly, we consider the frequency of the oscillation. At a lower one (figure 8), the frequency was lower when compared to the higher velocity (figure 9 or 10), in which the oscillation frequency was also higher.

Secondly, consider the magnitude of the hunting displacement from the experiment. At velocities of 6.70 m/s, 8.96 m/s, and 11.22 m/s, it was found that the average hunting displacements were 4.6 mm, 5.6 mm, and 6.8 mm, respectively. These agreed with the simulation results showing that the hunting displacement increases the velocity increases.

Finally, we consider the stable convergence of the wheelset. The results showed a difference between the two methods. By this instance of the research, the main factors will be the spring stiffness, damping coefficient, and the creep force coefficient that strongly affects the stability of both the experiment and the simulation results. These will be examined and considered to get the correct values at a later date.

4. Conclusions
In this work, a mathematical simulation model was developed for analyzing the influence of bogie component parameters that affect the stability of the railway vehicles. This work focused on hunting motion behavior. A scaled four-wheel railway bogie set was also constructed. This scaled railway bogie was able to demonstrate the bogie movement more easily and more safely than observing a real railway bogie operation, which is also prohibited due to safety rules of the company.

From the mathematical simulation model, we can ascertain the influence of each parameter that affects the hunting motion, by varying the parameter values. Also, when comparing the simulation results with the experimental results, we found both agreeing and conflicting results. However, the disagreeing results could be because of the still unknown exact parameter values. Therefore, the next step is to get the correct parameter values so the mathematical simulation model can predict and give reliable results.
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