Development of a simulation model of semi-active suspension for monorail

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Abstract. The new Kuala Lumpur Monorail Fleet Expansion Project (KLMFEP) uses semi-active technology in its suspension system. It is recognized that the suspension system influences the ride quality. Thus, among the way to further improve the ride quality is by fine-tuning the semi-active suspension system on the new KL Monorail. The semi-active suspension for the monorail specifically in terms of improving ride quality could be exploited further. Hence a simulation model which will act as a platform to test the design of a complete suspension system particularly to investigate the ride comfort performance is required. MSC Adams software was considered as the tool to develop the simulation platform, where all parameters and data are represented by mathematical equations; whereas the new KL Monorail being the reference model. In the simulation, the model went through step disturbance on the guideway for stability and ride comfort analysis. The model has shown positive results where the monorail is in stable condition as an outcome from stability analysis. The model also scores a Rating 1 classification in ISO 2631 Ride Comfort performance which is very comfortable as an overall outcome from ride comfort analysis. The model is also adjustable, flexible and understandable by the engineers within the field for the purpose of further development.

1. Introduction
The ridership of rail transport in the Klang Valley has increased significantly in recent years as it is perceived as one of the best mode of transportation systems compare to other forms of transport. This includes attributes such as safe, environmental friendly and low cost [1]. However, to remain a competitive means of transportation require increasing its operating speed. Higher speeds usually generate increased forces and accelerations on the current design of the monorail, which have a negative effect on ride comfort [2].

More so, in order to attract the public to use monorails as their preferred mode of public transport, ride comfort performance is a vital element to consider. Hence, the passenger ride comfort aspect becomes one of the considerations used by rail manufacturing companies. Semi-active technology in the suspension can be implemented to improve, or at least maintain, ride comfort at increased vehicle speeds or when track conditions are unfavourable.

One of the vital stage processes is computer simulation, where it can represent the improvement work on the semi-active suspension design with a complete set of part configurations represented mathematical equations. The optimization of semi-active suspension for the monorail specifically in terms of improving ride quality is continual improvement process and the simulation model which acts as a platform would be beneficial in improving the ride comfort.

In a computer model, semi-active suspension can be constructed and run on a typical or measured track in a virtual environment, with a wide range of possible designs or parameter changes to be
investigated. The attributes behaviour of the semi-active suspension and its interaction with any input response can be set up from the model.

Thus, in optimizing the monorail semi-active suspension, there is a need to have a platform to test the design of a complete set of suspension system particularly to investigate the ride comfort performance. It could also be the best virtual presentation before making it into an actual component and system. This paper intends to develop a simulation model of semi-active suspension for improving ride comfort for monorail system using simulation software (MSC Adams), which will then act as a platform for the optimization of the suspension for improving the ride comfort performance and to develop a data extraction base to evaluate the stability and ride comfort performance.

2. Overview on the new KL monorail

A monorail is a rail-based transportation system based on a single rail or beam. The term monorail also describes the beam on which the vehicle is travelling on. Generally, monorail serves as a track passenger or freight vehicles and travelling in either straddle beam or suspended guideways [3]. Monorail vehicles are wider than the guideway that supports them. KL Monorail (Malaysia) uses the straddle-type monorail as its public transportation modes [4].

The new 4-car KL Monorail is the product of the Kuala Lumpur Monorail Fleet Expansion Project (KLMFEP). On 30th November 2011, Syarikat Prasarana Negara Berhad (Prasarana) signed a RM 494 million contract agreement with Scomi Engineering Berhad, a subsidiary of Scomi Group Berhad, to provide 12 sets of new 4-car-trains for the existing KL Monorail line [5]. Scomi Engineering Berhad, a transport solutions provider is a division of Scomi Group Berhad based in Rawang, Selangor, Malaysia.

The KL Monorail is a straddle-type monorail based on the ALWEG (Axel Lennart Wenne- Gren). Usually straddle monorails have similar ALWEG suspension [6]. There are two suspension bogies, one at the front of each car and one at the rear. Both bogies consist of pneumatic tires on top for load and propulsion, and horizontal stabilizing pneumatic tires. The bogies also consist of dampers, springs, airbags and few more elements for suspension system.

The monorail rides on dual pneumatic rubber tire (drive wheel) and horizontal pneumatic rubber tires (guide wheels) for stability and guiding. The load wheel is larger in diameter than the guide wheel. The load wheels are steered (for curves) by the stabilizing wheels to prevent excessive tire tread wear [6]. In this system, the vehicle travels over the way of concrete beam of I section with a flat surface on the top for supporting and passage of the coaches’ wheel as shown in Figure 1.

![Figure 1. I-section beam shape [7]](image-url)
KL Monorail uses semi-active technology as their suspension technology system. Semi-active suspension usually utilizes controllable dampers of some kind, although the concept is not restricted to dampers. The benefit of the semi-active approach compared with full active is simplicity, because a separate power supply for the actuator is not needed [6].

A ride comfort control strategy is a set of discrete and specific measures identified and implemented to achieve improved ride comfort by optimizing the semi-active suspension. There are different control approaches possible for semi-active suspensions. In this study, the tuning of the measures namely damping and stiffness values has been done at all suspension elements such as springs, dampers, and airbags.

The ride comfort will be evaluated according to ISO 2631-1 in the present study. ISO 2631-1 is the standard evaluation of human exposure to whole-body vibration in terms of mechanical vibration and shock scope [8]. As this study is only on vertical motion, all the evaluation for ride comfort is on \( W_k \) – (vertical whole-body vibration, Z-axis (referred to Y-axis in the simulation), seated, standing or recumbent person) – as shown in Figure 2. Ride Comfort evaluation in ISO 2631-1 is divided to three categories of considerations which are based on the frequency ranges. The frequency ranges considered are 0.5 Hz to 80 Hz for health, comfort and perception, and 0.1 Hz to 0.5 Hz for motion sickness [8].

![Figure 2. Position of Passenger as in ISO2631-1 [8].](image)

3. Methodology

This section describes the method followed throughout this study. The CAD modeller SolidWorks was used to create the monorail beam and disturbance required for the simulation. The beam was constructed in a straight line or tangent in accordance as shown in Figure 3. A suitable input for stability and ride comfort analysis was chosen. 6 mm misalignment step disturbance as the input shape for stability and ride comfort analysis.

MSC Adams was used to simulate the KLMFEP KL Monorail on the constructed beam and disturbance for stability and ride comfort analysis. The template of the KL Monorail is obtained from Scomi Engineering Berhad. The template covers all the rigid bodies of components on the monorail including the joints, contacts and related works. However, the characteristics of the Monorail such as the bodies’ details, operating weight, forces and suspension component’s characteristics were not included. The template was constructed using SolidWorks and then imported into MSC Adams workspace. The beam and disturbance created earlier were imported from the SolidWorks file to the MSC Adams file.
The simulation characteristics were assigned into the template during setup stage. The characteristics include the bodies’ details such as mass, operating weight condition, forces applied and suspension component’s characteristics such as stiffness and damping. Vehicle weight was set at single car tare weight plus, 4 standing passengers per square meter as the weight condition for the simulation.

MSC Adams/View simulates the motions by referring to the force applied at any point. In perspective of speed, the speed is defined by the force applied. Thus, a correlation of forces and speeds were investigated using the interpolation method. The forces were then entered into the Step Function which was built by the Function Builder. A Single-Component Applied Force was used and the Run-Time Direction was On One Body, Fixed in Space. The floor of trailing car was being the body of application because the floor is at the center mass of the whole body. The point of application was at the floor of leading car. The direction of the floor was in Z-axis, parallel to the monorail. To make the simulation run smoothly, the end time and steps were also defined along the forces and speed correlation.

For stability analysis, the translational Y-displacement measurement was obtained in vertical axis from the centre mass of front bogie frame 2; namely Front_Bogie_Frame_cm_2. The original displacement graph was offset; defined by ‘Offset a Curve’ Button on the Post-Processor ribbon. This effectively resets the reference line or datum to 0.0 mm hence making the reading of the result easier.

For ride comfort analysis, the translational Y-acceleration measurement was obtained in vertical axis from the centre mass of car-body floor; namely Floor_cm_2. To obtain proper result, the translational Y-acceleration measurement for ride comfort analysis was filtered. The original acceleration curves were filtered and defined by Butterworth Filter in digital domain. The filter type used was Band Pass in Second Order (2) with Cutoff Frequency (Scaled) 0.1 to 0.9. The purpose of this filtering was to convert improper graph to a better or proper graph for analyzing the ride comfort.

Microsoft Excel was used to do the extraction works from the results obtained from the Adams/Post-Processor. It is used as the data extraction base. The base was divided into four parts which are; forces-velocity equations, parameter estimates equations, stability analysis and ride comfort analysis.

In stability analysis, the parameter estimates equations were built to calculate the damping ratio, damped frequency, natural frequency and angular frequency. Damping ratio is estimated using the Log Decrement Method. From the results of stability analysis obtained, the trends of the overshoot, settling time and damping ratio within the speed range were plotted. These trends with respect to frequency were used to conclude the stability of the KL Monorail as it travels along the tangent beam.

In ride comfort analysis, the acceleration in vertical motion of car-body floor was needed in order to calculate the frequency weighting and the Root Mean Square (RMS) Acceleration. The frequency weighted rms acceleration was then used to evaluate the ride comfort in accordance with the ISO.
2631-1 within the speed range. The frequency weighting curves that were used in the calculation of frequency weighted acceleration are provided in Figure 4.

![Figure 4. ISO 2631-1 Frequency Weighting Factors [9].](image)

Figure 5 denotes the graph which is used as the basis of evaluation for passenger’s health due to the vibration of the monorail as per ISO 2631-1:1997. The frequency weighted rms of the acceleration will be plotted against the graph to determine the effect of the vibration towards the health of train passengers. The health, motion sickness, comfort and perception results would provide an overall ride comfort performance of KL Monorail model in accordance with ISO 2631-1 standard.

![Figure 5. Health Guidance Caution Zone [9].](image)

3.1. Mathematical equations

The mathematical equations are divided into two parts i.e. for stability analysis and ride comfort analysis. The result of the finished simulations will appear in graphical form. As the suspension of the monorail is categorized as a second order system, the graph will be in transient response and in sinusoidal form. This is because the suspension system is in the underdamped motion

### 3.1.1. Mathematical equation for stability analysis

In stability analysis, the data required for the analysis are damping ratio, damped frequency, natural frequency and angular frequency as shown below:

Damping ratio is estimated from the Log Decrement Method;

\[
\sigma = \ln \left( \frac{|\text{Overshoot}|}{|\text{Undershoot}|} \right) = \frac{2\pi \zeta}{\sqrt{1-\zeta^2}}
\]  

(1)
Solving the above equation for damping ratio, $\zeta$.

Damping ratio:

$$\zeta = \frac{\ln \left( \frac{\text{Overshoot}}{\text{Undershoot}} \right)}{\sqrt{2\pi^2 + \ln \left( \frac{\text{Overshoot}}{\text{Undershoot}} \right)^2}}$$  \hspace{1cm} (2)

The frequencies of the system, damped and natural frequencies, are calculated using the following equations:

Damped frequency:

$$f_d = \frac{1}{T_d} = \frac{1/2}{T_u - T_p}$$  \hspace{1cm} (3)

Natural frequency:

$$f_n = \frac{f_d}{\sqrt{1 - \zeta^2}}$$ \hspace{1cm} (4)

Angular frequency:

$$w_n = 2\pi f_n$$  \hspace{1cm} (5)

3.1.2. Mathematical equation for ride comfort analysis

European standard EN 12299, which is a railway application of ISO, described well the ride comfort evaluating according to ISO 2631 [10]. The rms values of frequency weighted accelerations on the car-body floor level are evaluated as;

$$a_w = \left[ \frac{1}{T_0} \int_0^T a_w^2(t) \, dt \right]^{\frac{1}{2}}$$  \hspace{1cm} (6)

where:

$a_w(t)$ is the frequency-weighted acceleration (translational on this research) as a function of the time $t$ in m/s$^2$ in the z-direction (vertical) and $T$ is the duration of the measurement in seconds [9].

According to ISO2631-1:1997, motion sickness dose value (MSDV$_z$) is given by the following equation;

$$\text{MSDV}_z = \left\{ \int_0^T [a_w(t)]^2 \, dt \right\}^{\frac{1}{2}}$$ \hspace{1cm} (7)

4. Results and discussion

From the results obtained in the stability analysis, the overshoot, settling time and damping ratio were plotted against train speed to see the trend over different velocities as in Figure 6. From observation of the trends, the overshoot increases with speed. This is due to the inertia force contained in the monorail that pushed the bogie farther than the beam. Thus to ensure the stability of the monorail, an increase in damping is required which would lower the overshoots during higher running speed.

The vertical response behavior shows a faster settling time as the speed increases. However, the vertical results display higher peaks and shorter settling time. This is due to the large mass momentum of the vertical component. The suspension is forced to absorb and work between the rigid confines of the beam and train weight momentum acting vertically. The settling time reduces as the simulation speed increases. This is again due to phasing of the leading bogie and trailing bogie depending on the simulation speed.

Overall damping ratio for vertical response was low in magnitude but increases as the speed increases. This shows that the decaying of the oscillation due to the step disturbance increases which is also making the settling time decreases.
At speeds 20, 40, 60 and 80 km/h, the new 4-car KL Monorail has rating 1 which is very comfortable classification for the comfort and perception when it went through the step disturbance on the beam, as described in Table 1. However, at speed of 100 km/h, the monorail shows a rating 3 which is fairly comfortable classification for the comfort and perception in the same event. Note that normal maximum operating speed of the monorail is 80 km/h only.

| Speed (km/h) | 1 | 2 | 3 | 4 | 5 | 6 |
|--------------|---|---|---|---|---|---|
| 20           | ✓ |   |   |   |   |   |
| 40           | ✓ |   |   |   |   |   |
| 60           | ✓ |   |   |   |   |   |
| 80           | ✓ |   |   |   |   |   |
| 100          |   |   |   |   | ✓ |   |

All of positions on $W_k$ condition measured indicate a level which is below the health guidance caution zone corresponding to the assumed return journey time of 3 minutes. At a speed of 100 km/h,
it has recorded the highest vertical vibration among all speeds; however it does not exceed the health guidance caution zone. Therefore, it can be concluded that the new 4-car KL Monorail vertical vibration does not exceed the health guidance caution zone, as it is evident in Figure 7. The percentage of people who may vomit due to motion sickness varies from 1.67% to 2.16 %, with the highest percentage at the speed of 100 km/h.

This simulation result has been discussed at length with Scomi’s design engineers and test compared with the stability and ride quality reports done on the 4-car KL Monorail. It is deduced that this simulation model testing platform result consistent to actual measurement hence the results produced could be used for further studies.

5. Conclusion

This study was about the development of a simulation model of semi-active suspension for improving ride comfort for monorail. The new 4-car KL Monorail under KL Monorail Fleet Expansion Project has been the model for this simulation. The purpose of this simulation was to develop a model of the new 4-car KL Monorail using simulation software which will act as a platform for the optimization of the suspension for improving the ride comfort performance. This study comprises two types of analysis in order to obtain the overall ride comfort performance of monorail which were stability and ride comfort analysis. The ride comfort analysis could only be done if the monorail was proven to be in stable condition by the stability analysis. The results shown in Adams/Post-Processor were needed to go through several steps to obtain the required results.

The stability analysis results shows that the 4-car KL Monorail model is stable at its operating speed range while the ride comfort analysis results shows that the 4-car KL Monorail Model is rated at 1 classification which is very comfortable and its vertical vibration does not exceed the health guidance caution zone. The percentage of people who may vomit due to motion sickness is in low level.

This simulation results has been discussed with Scomi’s engineers and compared it with stability and ride quality reports done on KL Monorail. Thus a verification of these results was obtained from Scomi Rail Berhad. Therefore, this simulation model testing platform is valid and the results produced are reliable.

Overall, this study has achieved its objectives and this simulation model can be used for testing of vehicle’s stability and ride comfort for other monorails. All elements which contribute to ride comfort performance particularly on suspension configurations can be modified or tuned for getting the targetted results using this simulation platform. This simulation are adjustable, flexible and understandable by the engineers within the field and enable to continue in further development.
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7. **References**

[1] Szwarc, M., Kostek, B., Kotus, J., Szczodrak, M., & Czyżewski, A 2011 Problems of railway noise—a case study *International Journal of Occupational Safety and Ergonomics*, 17(3), 309-325.

[2] Ismail, M. A., & Said, M. N 2014 Integration of geospatial multi-mode transportation Systems in Kuala Lumpur. In *IOP Conference Series: Earth and Environmental Science* (Vol. 20, No. 1, p. 012027). IOP Publishing.

[3] http://www.spiritus-temporis.com/monorail/references.html

[4] *Scomi Monorail*. (2015). Retrieved from scomirail: http://www.scomirail.com.my/monorail.htm

[5] Prasarana. (2011). *Prasarana And Scomi Sign On KL Monorail Fleet Expansion Project*

[6] *Alweg*. (c2014). Retrieved from The Monorail Society: http://www.monorails.org/tmspages/TPAlweg2.html

[7] V.Dukkipati, R 2000 Vehicle System Classification in Vehicle Dynamics (pp. 10-11). *New Delhi: Narosa Publishing House*

[8] Scomi. 2010 *KLMFEP Monorail Ride Quality Test Report*

[9] Directorate, A 2012 Test Operations Procedure (Top) *01-1-014a Ride Dynamics And Evaluation Of Human Exposure To Whole-Body Vibration*

[10] Orvnäs, A. 2011. On Active Secondary Suspension in Rail Vehicles to Improve Ride Comfort. *Doctoral Thesis, KTH Engineering Sciences*