STUDIES AND SIMULATION of
THE TRAIN SUSPENSION SYSTEM

By

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the requirements for the

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CERTIFICATION OF APPROVAL

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A project dissertation submitted to the
Mechanical Engineering Programme
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Approved by,

____
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UNIVERSITI TEKNOLOGI PETRONAS

TRONOH, PERAK

NOVEMBER 2010

CERTIFICATION OF ORIGINALITY

This is to certify that I am responsible for the work submitted in this project, that the original work is my own except as specified in the references and acknowledgements, and that the original work contained herein have not been undertaken or done by unspecified sources or persons.

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MOHD HAIDZIR BIN ANUAR

ABSTRACT

Trains have evolved since the last century, yet, not much evolvement in suspension system. This old system needs some evaluation and validation. Simulation helps in evaluating and analyzing the current design. Simulating train suspension system in this project use simulation software called MATLAB SIMULINK. Basic concept of suspension system, vibration and simple model of spring-mass-damper was studied. This will help in developing the simulation model in the software. Within the MATLAB SIMULINK, block diagrams were used in order to build the simulation model. A set of spring and dampers parameters was used in the simulation of the suspension. Results produce from the simulation was analyzed to know its oscillation and time for it to return back to its initial position. This project is hope to create a platform for researcher and engineer in analyzing and evaluating engineering system especially in train suspension system and also attracts more people to invest in the development of local train industry here in MALAYSIA.

ACKNOWLEDGEMENT

Praise to Almighty God, because of giving me this opportunity to complete this project. Then, to my supervisor, Dr. Vu Trieu Minh, thanks a lot for the advise, help, comment, and useful tools to me along the progress of the project until the project completed.

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CHAPTER 1
~ INTRODUCTION ~

1.1 PROJECT BACKGROUND

Trains have been used since the age of steam engine. It had evolved since that time and has become one of the important transportation in most of the country around the world. Even in Malaysia, train is one of the main transportation for its people to move from one state to another. Development had been done day by day to improve the major aspect in any public transportation which is the safety, riding quality and comfort. In respect of all train designs, it use bogie to support the train's body.

A bogie is a structure underneath a train. Usually two bogies are fitted under one carriage (body), one at each end. In the modern types of bogie, the placement of it are different depends on the type of the train being build. Inside the bogie there is suspension system which has function mainly to provide comfort and pleasure. The specific functions of these suspensions are to isolate the forces generated by the track unevenness, to control of train body with respect to track surfaces and to maintain the suitable space between track and train body.

There are two types of suspension in the bogie. The primary suspension located between the wheel and the bogie while the secondary suspension located in the space between the bogie and the train body. Suspension system in a bogie mainly consists of coil spring, shock absorber and rubber airbag. Different bogie has a different design placement of the coil spring and the dampers. Suspension system also were use to permit the rotational movement of the bogie by taking the advantage of the sideways movement of the suspension. The spring that is used has many kinds and some of it is conical springs, chevrons springs, laminated pads, system including bushes.

Suspension system can be simulating using simulation whether it is hardware of software. Software simulation is widely use in today's engineering. This is because, it is much cheaper in order to analyze and study an engineering system. It provide a platform to predict the real situation before the system been build and execute. MATLAB SIMULINK is one the simulation software that is available outside.

Thus, this project is made to study the train suspension system and develop a simulation model using MATLAB SIMULINK as it simulation software. This simulation is then could lead us to the improvement of the current train use as public transport.

The importance of this project are to provide a new platform in analyzing a mechanical system (in specific is the train suspension system) and to open and attract more research in developing and improve current train model in Malaysia which is widely use as public transport.

1.2 PROBLEM STATEMENT.

Today's trains are still bumpy and not smooth and Malaysia is not excuse from it. Ride quality mostly depends on the suspension performance. Noise from vibration due to the force from the unevenness of rail track could be minimize or isolate by suspension system. In development and improvement of a train, suspension is a major component that needs to be considered. It provides comfort, handling performances and ride safety.

The problem now is how to evaluate the current suspension performance in order to improve it? There is no specific evaluation method that can be use. If there is a method, are they cheap? Problems in hardware simulation are there are much expensive. Simulation using software is much cheaper and has been use widely in today's engineering analysis. Software simulation also could help us in evaluating the current engineering system in order to improve or design it.

This project would deal in study and development of computer simulation that could simulate the condition of existed train's suspension system. This could help in development and improvising today's train suspension so that it would meet the objective of the suspension itself & provides optimum results towards the performance of the train.

1.3 OBJECTIVE & SCOPE OF STUDIES

The objectives of this project are:

1. To study the train suspension system & the rail track condition.
2. To produce simulation model of train suspension system using MATLAB SIMULINK software.
3. To propose suggestion to improve the current train suspension system model.

The scope of this project will be around the Passenger's train that consists of the bogie and its suspension system. After studying the suspension system, the project continues with the development of dynamic model of the suspension system and produces the equation of motion that describes the train suspension system. MATLAB SIMULINK software will be use to assist the creation of simulation of the suspension system. Based on the equation of motion of the suspension system, the simulation model is build inside the software. The results are to describe the motion of the suspension system towards the bogie and train's body by applying a certain input force. Improvements are proposed towards the current model of the train suspension model.

CHAPTER 2
~ LITERATURE REVIEW ~

Although today's trains are faster, lighter and more reliable compare to century ago, there are still less research been done specifically on optimal design of railway vehicle (train suspension) [1]. Designer or research mostly done by a company and been kept as trade secret. Usually, designs are concern on aerodynamic, materials, engine and fuels to make the train run faster. Recently, designer and researchers have take the suspension are their major consideration [2].

In Malaysia, although trains have been used throughout decades ago, yet, there are still lots of room of improvement can be made. Mostly the trains are made by foreign company and bought by Malaysia. In the last 5-10 years ago, trains have become more concern by the government and government related company (GNC). Research, designer and engineer that specialize in trains have become demand to ensure trains in Malaysia could be improve and development so that it able to compete with other country such as Germany or Japan. Recently, Minister of International Trade and Industry, Datuk Seri Mustapa Mohamed had said that "Malaysia is still new in this industry and our universities have not produced such engineer" and "today there are demands to have train's engineer and this is the sector that we need to add more specialize" [3].

This paper is made to support the word of the minister in adding more engineers in trains and research done on trains. Here it focuses on suspension system of the train.

SIMULINK is use as the platform in constructing the simulation model and in this section, it will cover several topic related to suspension from what had been read to gain info and understanding about the suspension system and simulation.

2.1 TRAIN'S BOGIE & SUSPENSION SYSTEM

A bogie (pronounced /ˈboʊgi/, us dict: bō′·gē) is a wheeled wagon or trolley. In mechanics terms, a bogie is a chassis or framework carrying wheels, attached to a vehicle. It can be fixed in place, as on a cargo truck, mounted on a swivel, as on a railway carriage or locomotive, or sprung as in the suspension of a caterpillar tracked vehicle [4]. The bogie itself consists of certain components which are the frame, suspension system, wheel set, brake equipment, and transmission (for certain electrical trains). The bogie itself have some purpose which are to support the rail vehicle body, to add stability on straight and curve track, to ensure the ride comfort and to minimize the generation of track irregularities and rail abrasion. The components in bogie are related with each other and in order to evaluate one component such as suspension system, other's components also need to be included in the analysis.

In this project, components that involve in developing and constructing the simulation mostly are the wheels, suspension system itself, bogie and the train body. These are the components to consider. In order to simplify the simulation, only vertical motion is consider to be analyzed and simulate as this is the motion that contribute to the ride comfort of a passenger train. This consideration helps in simplify the analysis done throughout the project.

In the other hand, for suspension and based on a book, it said, *It was recognized very early in the development of railways that the interface between vehicle body and wheel needed some sort of cushion system to reduce the vibration felt as the train moved along the line* [5]. The development of bogie's suspension system had evolved over many years and it is a difficult and complex sciences. The first design of suspension is using the leaf spring. It consists of a stack of different length of steel plates. There were a number of suspensions systems such as leaf spring suspension, coil spring suspension, rubber suspension equalizer suspension and air suspension.

In the passenger type bogie, the main component in suspension system consists of two suspensions which are the primary suspension (usually at the wheel set or lower bogie frame) and secondary suspension (use to support the train body). Both suspension systems are analyzed as the spring-mass-damper system. Analyzing this type of system could help in determine the vertical or bouncing motion of the train body.

Principal functions of the primary suspension are guidance of wheelsets on straight track and in curves, and isolation of the bogie frame from dynamic loads produced by track irregularities. The secondary suspension provides the reduction of dynamic accelerations acting on the car body which determines passenger comfort [6]. So, its importance to know analyze the suspension's system of a train so that this principal functions could be achieves. The suspension system is not only use springs but dampers. Hydraulic dampers are almost universally used in passenger bogies and sometimes also in modern freight bogies [7].

The arrangement and function stated above is made for passenger bogie which mainly concentrating mostly on the ride quality of the passenger. That is why it has two type of suspension so that it could eliminate most of the forces due to the track. Different type of train use different type of bogie which have different arrangement, numbers of suspension and function. This project is focusing only on public transport which is the passenger type.

2.2 FORCES AND TRACKS

In simulating the train's suspension system, there is a need to consider the physical aspect of the railway system. This is to ensure the simulation models are within the real condition and relevance to the railway system. Forces and tracks condition are the physical aspects that would be discussed further.

As a beginning, in simulating the train's suspension system, the force paths that exert by the train should be examine. These forces is important to be examine as they contribute in producing the vibration force to the train and the purpose of the suspension is to isolate this force of vibration. Studying the force path also would help in development of the train model. Let consider the diagram below to illustrate the force paths of a train.

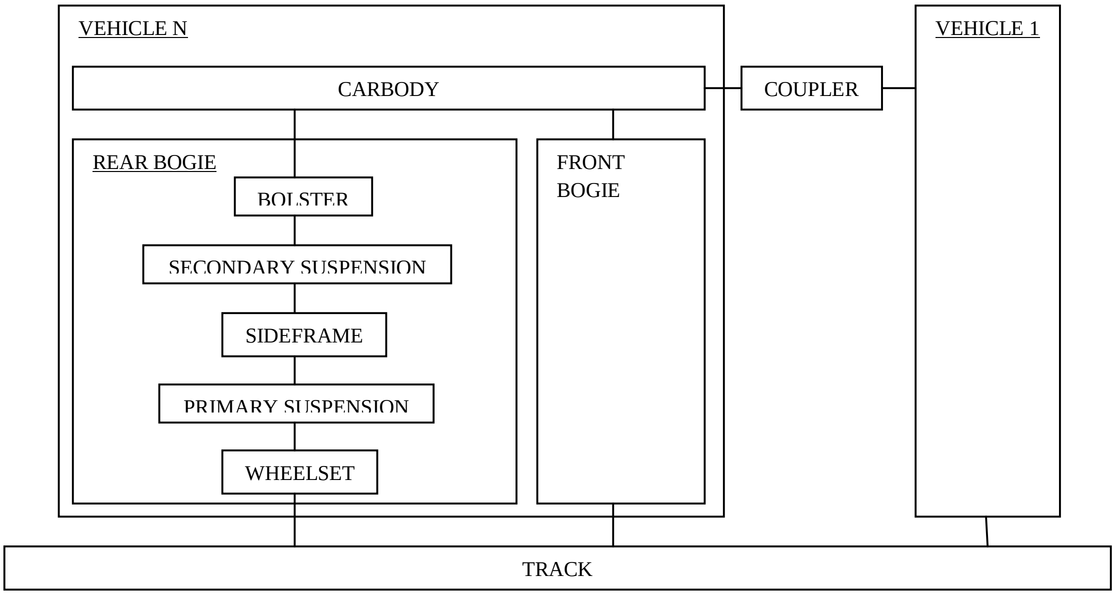


Figure 1 Force Paths of a Train [8]

A simple example could be explain from here where the load of the car body weight are transmitted from upward to downward which will go through the bolster, secondary suspension, sideframes, primary suspension, wheelsets and lastly to the track. There are also forces from the track due to the irregularities and track's nominal geometry which will transmitted the force from downward to the carbody through all the middle components stated before. Based on the study of these forces, we could model the movement of each of the component involve to build the train model. Usually, a free body diagram will be constructing.

Another thing to consider is the track itself. Trains use track as its platform to move from one place to another just like cars use road. Tracks in simulation of suspension system act as an input. These will provide the simulation with different kinds of inputs as there are types of tracks condition. Some of the tracks condition that could be list up here are, superelevation, spiral, reverse curve, grade, and track irregularities. Besides that, the force from the track could affect the passenger and the performance of the train as what been wrote in Computer-Aided Simulation in Railway Dynamics" which are, *Trains operations and performance are dependent to a great extent on the track condition since train equipment and loading damage can result from improperly constructed or deteriorated track* [9].

There are four common parameters that could define track irregularities such as alignment, gauge, cross level and vertical profile [10]. Based on book written by Rao V. Dukkipati[11], the definition of the alignment is the average position of the left and right rails while gauge is the distance of the left and right rails. Cross level is the difference in elevation between two rails (left and right) and vertical profile is the average elevation of two rail position (left and right). In appendix section, there is a figure that show the rail track condition which been stated before.

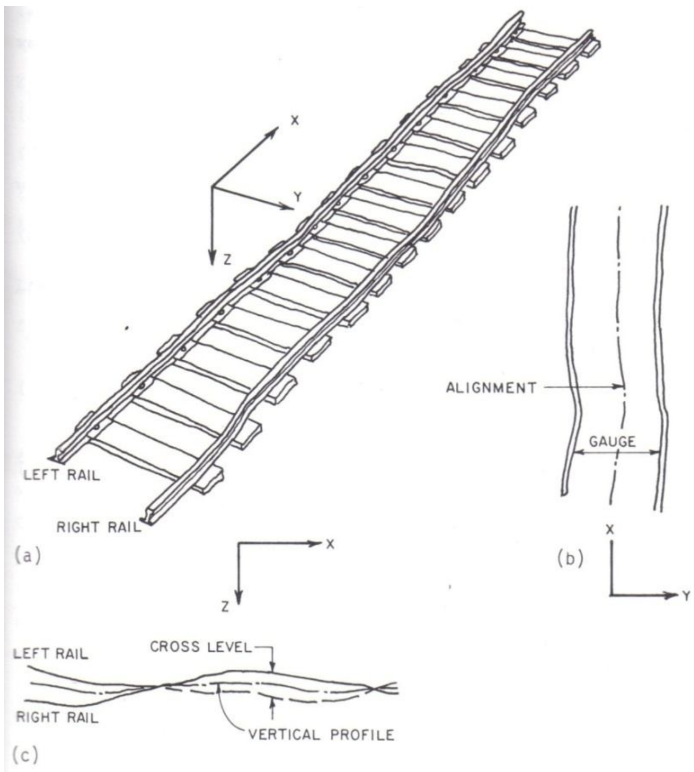


Figure 2 Track Irregularities, (a) Track Layout, (b) Gauge & Alignment, (c) Cross-Level & Vertical Profile

2.3 PASSENGER BOGIE (TRUCK)

The passenger bogie consists of main components which are the wheelsets, primary suspension elements, bogie frame and secondary suspension elements. The primary suspension usually use coil springs with rubber nests and sometimes use vertical dampers. There are also others bogie that use coil spring with flexible links from axle boxes to the frame. Primary suspension mainly located at the axle boxes. The secondary suspension is located between the bogie frame and the car body. It supports directly or through bolster. Generally, like the primary suspension, it use coil spring and vertical dampers. In secondary suspension, there is also lateral suspension which usually provided by swing links and hydraulic dampers. Example can be seen in The Budd Pioneer 3 which uses lateral dampers in its bogie. Nowadays, commonly, passenger bogies would use hydraulic dampers and sometimes also been use in modern freight bogies.

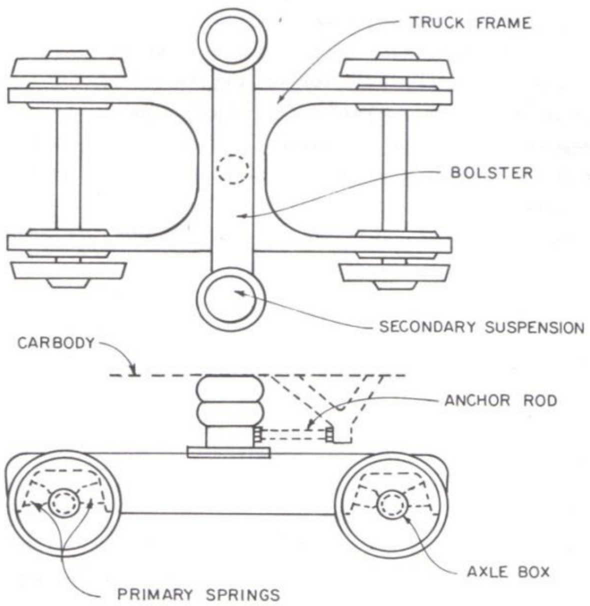


Figure 3 Passenger Bogie Configurations

2.4 TRAIN MODELING

Modeling a physical system is the early step in analyzing vibration problems. Suspension mainly deals with vibration. In simulating the train suspension, the physical systems of it need to convert into a model that called the mathematical model. This model is likely to be in the form of a free body diagram system. The purpose of this model is to represent all the important features of the system for the purpose of deriving the mathematical equations governing the system's behavior [12]. Below are shown the physical system of the suspension train of a passenger train.

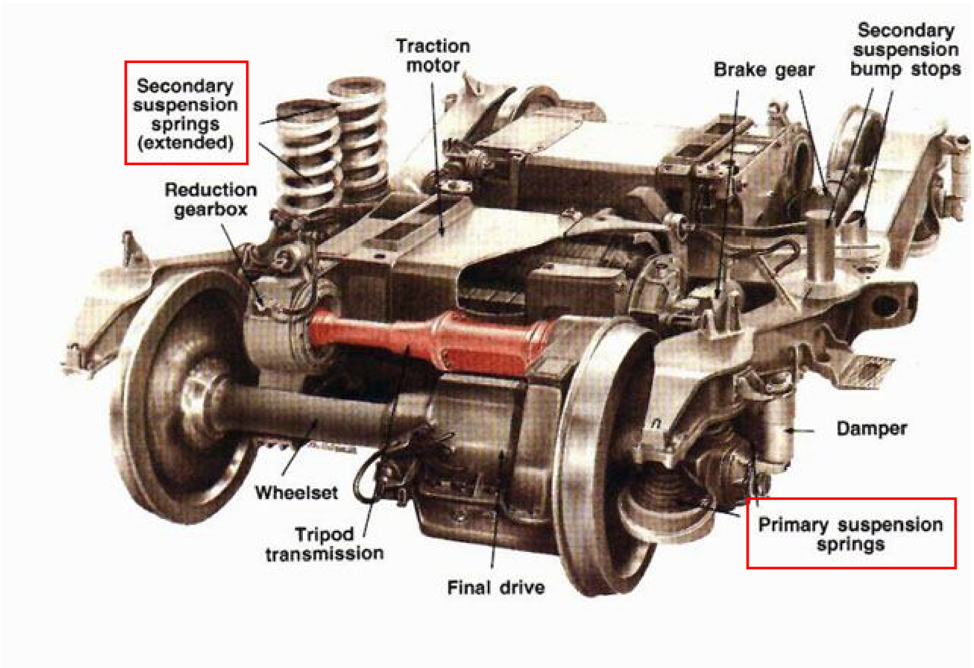


Figure 4 Example of Passenger Bogie

Based on the physical system, all the important features which is the frame, primary and secondary suspension could be converting into the mathematical model such as the free body diagram. Not to forget the train body also. The train model is then would look like the picture below;

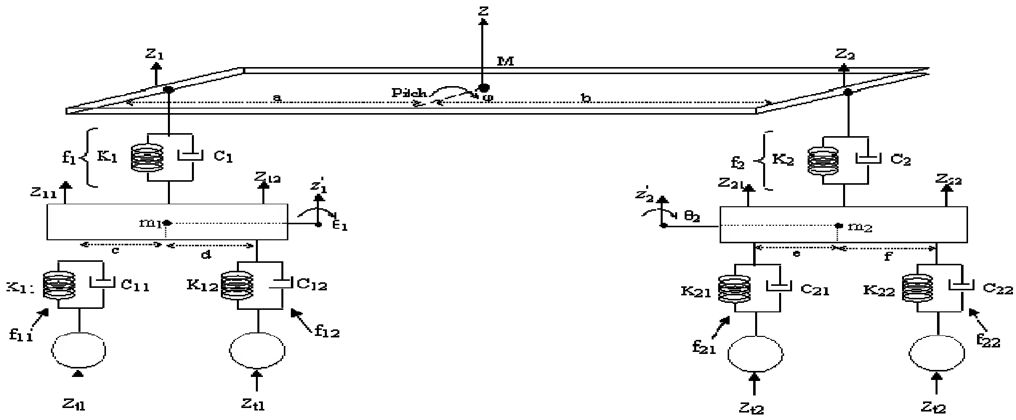


Figure 5 Example of Train Model (Free Body Diagram) based on the passenger train.

From here, the equation of motion could be derived using the principles of dynamics. The next section will cover more about this. Basically, the model will look like the spring-mass-damper model as it is common to use this model in vibration analysis.

There are also many types of model that could be considered in analyzing the physical system. There are full model, half model and quarter model. Full model will consider all components involve. Whereby, half model only considers one side of the train and quarter model only consider front side or back side of the system. It just like a cube in 3D was divides into four sections. Each section represents a quarter models. Each model has different way in analyzing them. Full model is more complex than half model and quarter model is simpler than both full and half model. In this project, half model is considered as the train is assuming to be symmetry. This will help in simplifying the analysis.

In the term for degree of freedom, it is define as the minimum number of independent coordinates required to determine completely the positions of all parts of a system at any instant of time [13]. Referring to the figure 5 above, it can be said that the train body and the bogie each have two degree of freedom. This is associated with the bounce and pitch motion. Overall degree of freedom of the train would be six degree of freedom.

2.5 EQUATION OF MOTION USING NEWTON'S 2ND LAW OF MOTION

In developing the simulation model of the train's suspension system, there are several methods that could be use which are the Newton's 2nd Law of Motion, Lagrange's equation and etc. This project used the Newton 2nd Law of Motion since it is simpler compare to the other method. In using the Newton's 2nd Law of Motion, first of all, a free body diagram (like in the previous section) needs to develop. In this section, a simpler model of free body diagram will be us as example of a free body diagram like the one shown below. This is to make the understanding easier.

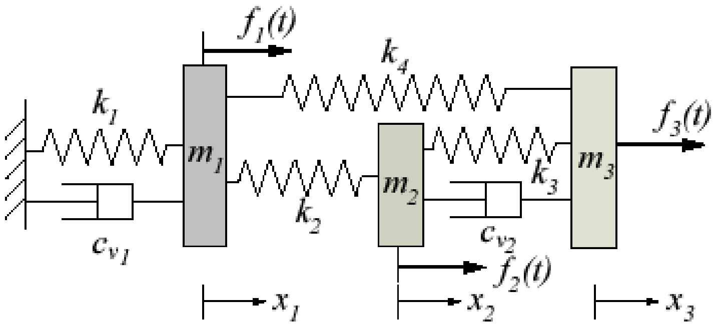


Figure 6: Example of Free Body Diagram

The equation of motion of this example could be derive using the Newton's 2nd Law of Motion, F = m*a. Each of the mass involve in the free body diagram will be evaluate based on the Newton's 2nd Law to produce one equation for each mass. This could be shown as below;

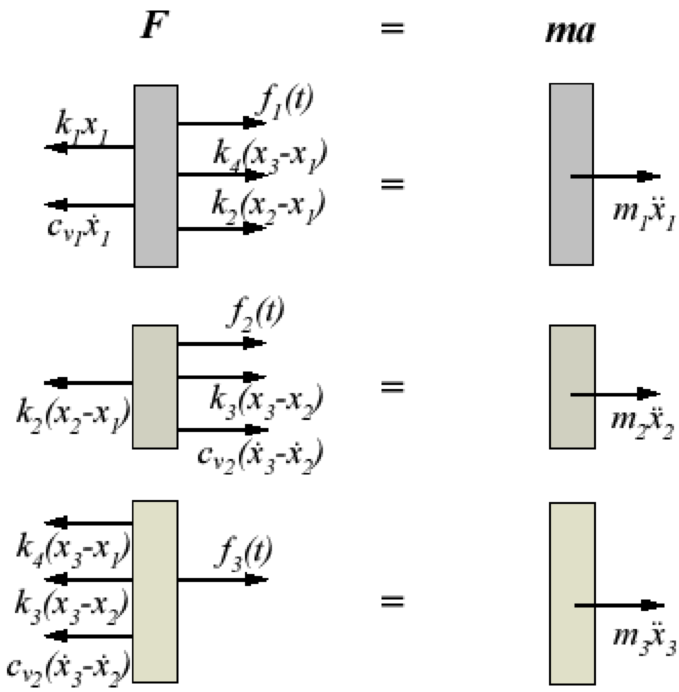


Figure 7: Evaluation of each masses using Newton's 2nd Law of Motion

From the above evaluation, the equation of motion for each of the mass could be expressed like the one shown below;

$$m_1\ddot{x}_1 + c_{v1}\dot{x}_1 + (k_1 + k_2 + k_4)x_1 - k_2x_2 - k_4x_3 = f_1(t)$$
$$m_2\ddot{x}_2 + c_{v2}\dot{x}_2 - c_{v2}\dot{x}_3 + (k_2 + k_3)x_2 - k_2x_1 - k_3x_3 = f_2(t)$$
$$m_3\ddot{x}_3 + c_{v2}\dot{x}_3 - c_{v2}\dot{x}_2 + (k_3 + k_4)x_3 - k_3x_2 - k_4x_1 = f_1(t)$$

Equation 1: Example of Equation of Motion

This derivation of equation will help in building the simulation model in the MATLAB SIMULINK. Each of this equation already represents each of the mass in the free body diagram. This equation also can produce the acceleration, velocity and displacement of each of the mass.

2.6 SIMULATION IN MATLAB SIMULINK

MATLAB is one of the software uses today as a powerful technical computing tool. MATLAB can be used as a very sophisticated calculation tool, as a lower-level engineering programming language, or as a high-level graphical programming language (through its SIMULINK interface) [14]. It has variety of function for mathematical, graphical and engineering applications with specialized toolboxes for targeted applications.

SIMULINK which build inside the MATLAB, is another method for automatic computation but more complex than the previous method describe. It use block diagram to describe an engineering computation. In Math Works website, SIMULINK is defined as *an environment for multidomain simulation and Model-Based Design for dynamic and embedded systems. It provides an interactive graphical environment and a customizable set of block libraries that let you design, simulate, implement, and test a variety of time-varying systems, including communications, controls, signal processing, video processing, and image processing [15].*

In Simulink, data/information from various blocks are sent to another block by lines connecting the relevant blocks. Signals can be generated and fed into blocks (dynamic / static). Data can be fed into functions. Data can then be dumped into sinks, which could be scopes, displays or could be saved to a file. Data can be connected from one block to another, can be branched, multiplexed etc. [16]

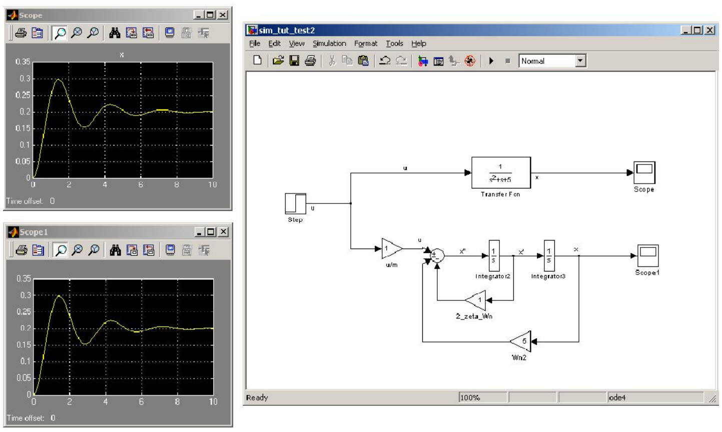
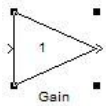


Figure 8: Sample of spring-mass-damper simulation in SIMULINK

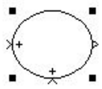
There are many types of block diagram that could be use in building the simulation model. Simulation model could be in continuous systems or discrete systems. Suspension systems is a continuous system and there are certain block diagrams that mostly been use for this kind of systems. In order to make things to be understand easier, a simple model will be use to explain the usage of the block diagrams.

There are four primitive blocks used to represent continuous linear systems which are gain block, sum block, derivative block and integrator block. The function of each block is summaries in the list below.

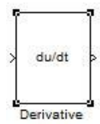
- Gain block – the output of the gain block is the input multiplied by a constant. The block represents the algebraic equation,$y = kx$.



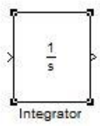
- Sum block – permits to add two or more inputs. It represent the algebraic equation $c = a - b$.



- Derivative block – computes the time rate of change of its input. It represents the differential equation, $y = \frac{dx}{dt}$.



- Integrator block – computes the time integral of its input from the starting time to the present. It represents the equation, $y(t) = y(t_0) + \int_{t_0}^{t} x(\tau)d\tau$.



Based on this four block diagram, a simple simulation of a spring-mass-damper could be build. Taking the model below and derive the equation of motion as what been describe earlier, we will get;

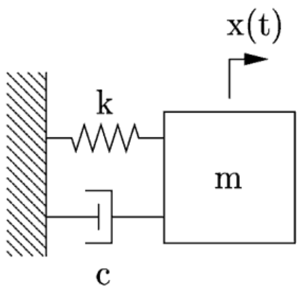


Figure 9 Spring-Mass-Damper model

$$m\ddot{x} + c\dot{x} + kx = 0 \quad (1)$$

This equation is a second-order system and it need to integrator in order to solve it which the final result that will able to get is the displacement of the mass. The output of the Velocity integrator is $\dot{x}$, so its input must be $\ddot{x}$. Rewrite the equation of motion to compute $\ddot{x}$ as a function of x and $\dot{x}$:

$$\ddot{x} = -\frac{c}{m}\dot{x} - \frac{k}{m}x \quad (2)$$

From this final equation, the simulation model can be build using the four block diagram that had been mention earlier and it will produce something like the example below;

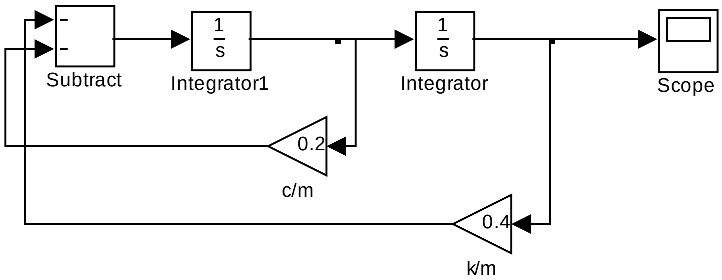


Figure 10 Simulation model in SIMULINK

After building the simulation model, the simulation can be run and the result for this simple example of mass-spring-damper model as shown below.

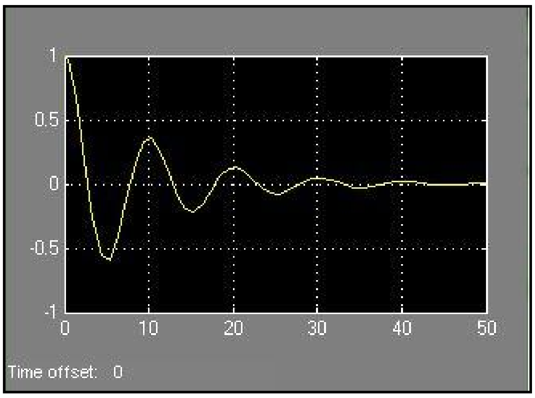


Figure 11 Spring-Mass-Damper model response.

CHAPTER 3

~ METHODOLOGY ~

3.1 PROJECT ACTIVITIES

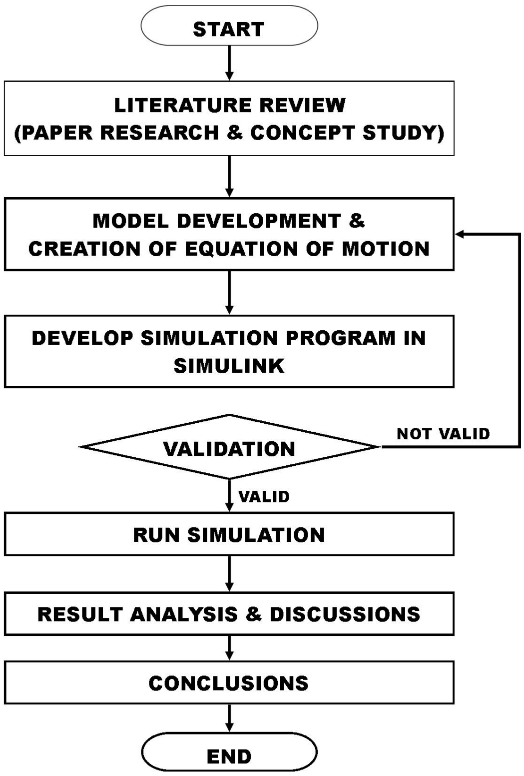


Figure 12 Flow Chart of Project Activities

Figure 10 above show about the flow chart of the project activities that had been carried out throughout the year. After this, the next section will briefly explain about each and every step in the flow chart. This flow chart had been developed at the beginning of the project and it also had been changes in time to time as more finding and info had gain and changed the step taken in completing this project.

3.2 STUDY ON SUSPENSION, VIBRATION, E.O.M. AND SIMULINK

In this step, more research, reading and learning involve as to get the information about suspension, vibration, equation of motion (EOM) and SIMULINK. Lots of research had been done to find journals, articles, thesis and etc about the train suspension system analysis. The suspension system is only one part of plenty of component involve in the dynamic analysis of the train. This limit the source and not many sources could be found that only focusing on the suspension system.

Suspension system is a mechanical system that related with vibration. This has brought this step on study to gain information and learn about the basic concept in vibration and also step taken in analyzing the vibration problems. Vibration studies also had brought into another area of study which is the dynamic where it helps in deriving the equation of motion that need to describe the vibration system of the train suspension.

Along the way also, research and study on SIMULINK software were made. This had been done by finding books, tutorials, discussion with colleague and lecturers and try and error in the software itself. Familiarization also are another important part in this step as it help in building the simulation model based on the equation of motion. Most of all the sources of research and reading are available in the references section.

3.3 MODEL DEVELOPMENT & CREATION OF E.O.M.

After study the suspension system and all the related subject, the model of the suspension is develop. Basically the model represents the free body diagram of the suspension system which includes the suspensions, bogies (front and back) and the train body. This model is shown in the result and discussion section.

Before getting to the final model which is the half model of the train suspension system, the model was start by developed the quarter model first. As the quarter model is simpler than the other half and full model, this help in validation of the model. After completing the quarter model and had pass the validation by running it in the SIMULINK, the half model was developed. The train is assuming to be symmetry, so the full model was not developed in this project.

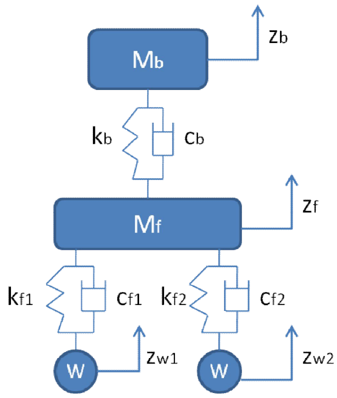


Figure 13 Quarter model of the Train Suspension System

After complete the development of the quarter model, the equation of motion was derived using the dynamic principle of Newton's 2nd Law of Motion. By this equation, the simulation model was built in the SIMULINK. As been said before, after validate the simulation of the quarter model, the work proceed with the development of the half model.

Taking the example of quarter model above, the equations of motion are;

For body, M_b,

$$m_b\ddot{x}_b + k_b(z_b - z_f) + c_b(\dot{z}_b - \dot{z}_f) = 0 \quad (3)$$

For left wheel, W_l,

$$m_{f1}\ddot{z}_{f1} + k_{f1}(z_{f1} - z_{w1}) + c_{f1}(\dot{z}_{f1} - \dot{z}_{w1}) - k_b(z_{f1} - z_b) - c_b(\dot{z}_{f1} - \dot{z}_b) = 0 \quad (4)$$

For right wheel, W_r,

$$m_{f2}\ddot{z}_{f2} + k_{f2}(z_{f2} - z_{w2}) + c_{f2}(\dot{z}_{f2} - \dot{z}_{w2}) - k_b(z_{f2} - z_b) - c_b(\dot{z}_{f2} - \dot{z}_b) = 0 \quad (5)$$

From here, each of the equations is made as reference in development of the simulation model in SIMULINK which will be explain further in the next section.

3.4 SIMULATION MODEL DEVELOPMENT IN SIMULINK

This step involves completely using SIMULINK block diagram. Full step of building a simple model to solve a differential equation is available in the appendix. The step is likely to be the same but are more complex as the quarter model deal with a higher degree of freedom.

More special block diagram were used in order to build the half model.

3.5 VALIDATE

After completing development of the simulation model for quarter model of the train suspension system, the model is validate. Validating process is based on the response of a simple model of mass-spring-damper system. If the response of the quarter model has the same structure as the mass-spring-damper system, so the simulation model is correct. The project was proceed by developing the half model. The same steps were taken in validating the half model system.

3.6 RESULT ANALYSIS & DISCUSSIONS

After complete built the half model of the simulation model of the train suspension system, the final results were analyzed. Analyze was done by finding the response that have the less amount of oscillation. This will determined the passenger comfort.

CHAPTER 4

~ RESULT & DISCUSSION ~

4.1 FINAL TRAIN MODEL

During the early stage of this project, the train model had evolved from a single degree of freedom (a spring-mass-damper model) to a quarter models (only front component being developed) and lastly the half model of the train suspension had been developed. Below is the diagram of the train model.

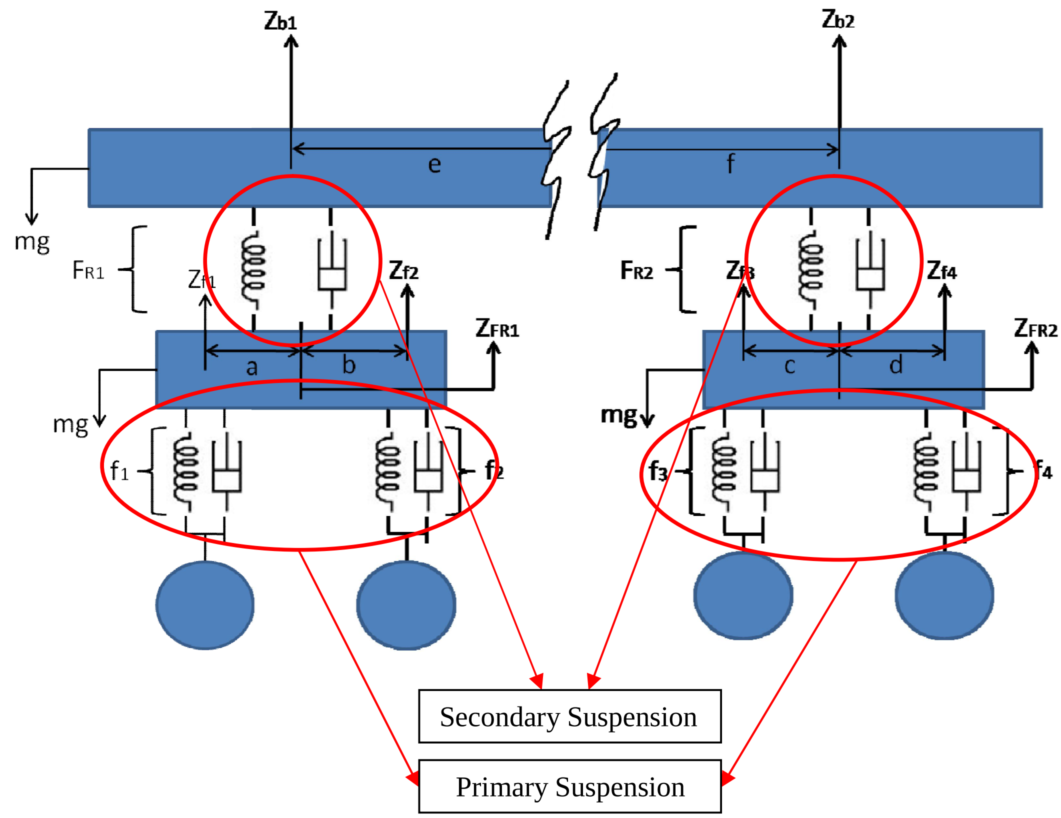


Figure 114 Final Train Model

This model is then use to assist in developing the equation of motion.

4.2 FINAL EQUATION OF MOTION

Based on the final train model in the previous section, the equation of motion for each mass are build. The equations are as below;

Longitudinal Body Acceleration,

$$m_b\ddot{z}_b + F_{R1} + F_{R2} = m_b g \quad (6)$$

$$\ddot{z}_b = \frac{-F_{R1} - F_{R2} + m_b g}{m_b} \quad (7)$$

Where

$$F_{R1} = C_{b1}(\dot{z}_{b1} - \dot{z}_{FR1}) + (z_{b1} - z_{FR1}) \quad (8)$$

$$F_{R2} = C_{b2}(\dot{z}_{b2} - \dot{z}_{FR2}) + (z_{b2} - z_{FR2}) \quad (9)$$

Longitudinal Front Bogie Acceleration,

$$m_{F1}\ddot{z}_{FR1} + f_1 + f_2 = F_{R1} + m_{f1} g \quad (10)$$

$$\ddot{z}_{FR1} = \frac{-f_1 - f_2 + F_{R1} + m_{f1} g}{m_{f1}} \quad (11)$$

Where

$$f_1 = C_{f1}(\dot{z}_{f1} - \dot{z}_{w1}) + K_{f1}(z_{f1} - z_{w1}) \quad (12)$$

$$f_2 = C_{f2}(\dot{z}_{f2} - \dot{z}_{w2}) + K_{f2}(z_{f2} - z_{w2}) \quad (13)$$

$$F_{R1} = C_{b1}(\dot{z}_{b1} - \dot{z}_{FR1}) + K_{b1}(z_{b1} - z_{FR1}) \quad (14)$$

Longitudinal Rear Bogie Acceleration,

$$m_{F2}\ddot{z}_{FR2} + f_3 + f_4 = F_{R2} + m_{f2} g \quad (15)$$

$$\ddot{z}_{FR2} = \frac{-f_3 - f_4 + F_{R2} + m_{f2} g}{m_{f2}} \quad (16)$$

Where

$$f_3 = C_{f3}(\dot{z}_{f3} - \dot{z}_{w3}) + K_{f3}(z_{f3} - z_{w3}) \quad (17)$$

$$f_4 = C_{f4}(\dot{z}_{f4} - \dot{z}_{w4}) + K_{f4}(z_{f4} - z_{w4}) \quad (18)$$

$$F_{R2} = C_{b2}(\dot{z}_{b2} - \dot{z}_{FR2}) + K_{b2}(z_{b2} - z_{FR2}) \tag{19}$$

Referring to all of the above equation, the value for $z_{b1}, z_{b2}, z_{f1}, z_{f2}, z_{f3}, and\ z_{f4}$ can be find by using the moment equation. The equations are;

$$z_{b1} = z_b + e\theta_b \tag{20}$$

$$z_{b2} = z_b - f\theta_b \tag{21}$$

$$z_{f1} = z_{FR1} + a\theta_{FR1} \tag{22}$$

$$z_{f2} = z_{FR1} - b\theta_{FR1} \tag{23}$$

$$z_{f3} = z_{FR2} + c\theta_{FR2} \tag{24}$$

$$z_{f4} = z_{FR2} - d\theta_{FR2} \tag{25}$$

Other than longitudinal motion, there are also pitch motion that can be considered in the simulation of the train suspension system. This motion can be derive from the moment equations. The equations are;

Pitch motion, Front Bogie,

$$J_{F1}\ddot{\theta}_{FR1} = T_{f2} - T_{f1} = bf_2 - af_1 \tag{26}$$

Pitch motion, Rear Bogie,

$$J_{F2}\ddot{\theta}_{FR2} = T_{f4} - T_{f3} = df_4 - cf_3 \tag{27}$$

Pitch motion, Body,

$$J_b\ddot{\theta}_b = T_{FR2} - T_{FR1} = fF_{R2} - eF_{R1} \tag{28}$$

All of the equations are than being referred to build the simulation model in the SIMULINK.

4.3 SIMULATION MODEL (SIMULINK PROGRAMMING)

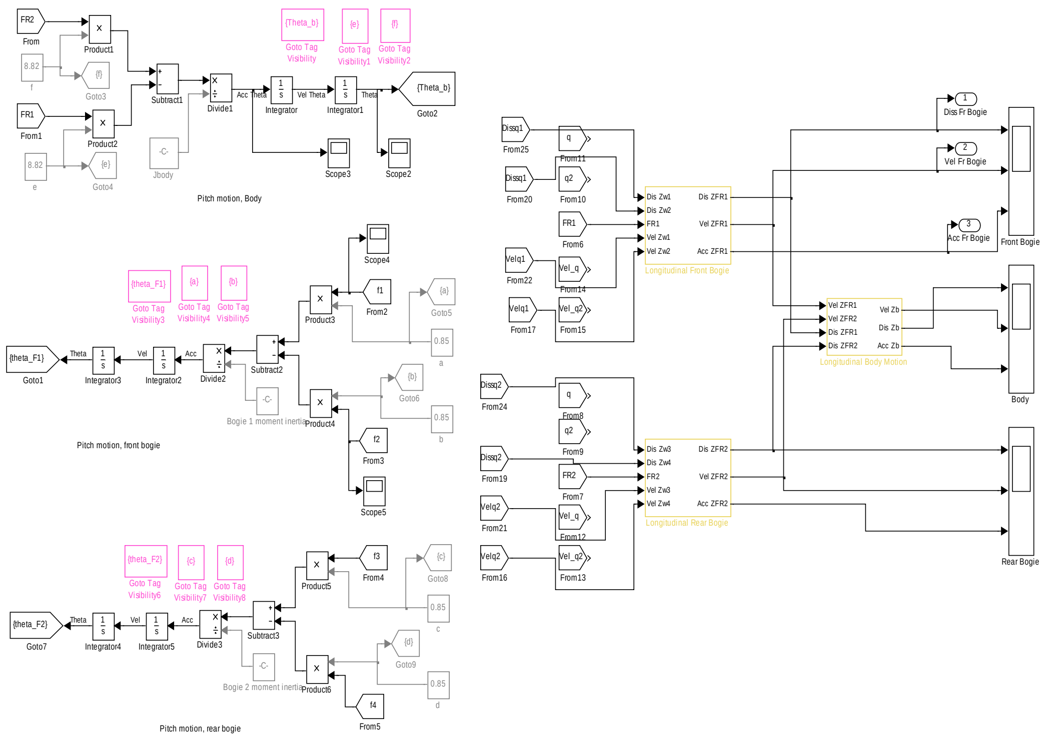


Figure 15 Block Diagram of Simulation Model

Each of the equations (longitudinal body acceleration, longitudinal front bogie acceleration, longitudinal rear bogie acceleration, pitch motion front bogie, pitch motion rear bogie and pitch motion body) are considered as a subsystem which become the main system when combine together as one. As what the figure 13 is all about, it show the whole structure system of the simulation model.

Basically the subsystem for longitudinal motion (for front bogie, rear bogie and body) are quit the same and it is shown as the diagram below;

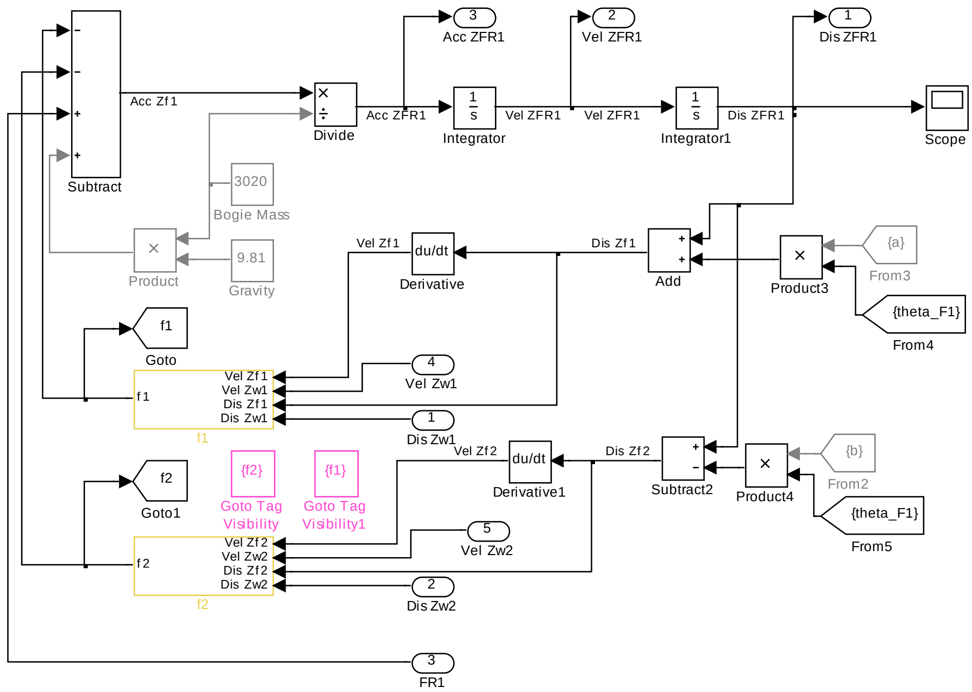


Figure 16 The subsystem for Longitudinal Motion for Front Bogie

Inside this longitudinal subsystem, there is also another subsystem which represents the parameters of the suspension such as springs and damper. The subsystem can be visualized as diagram below;

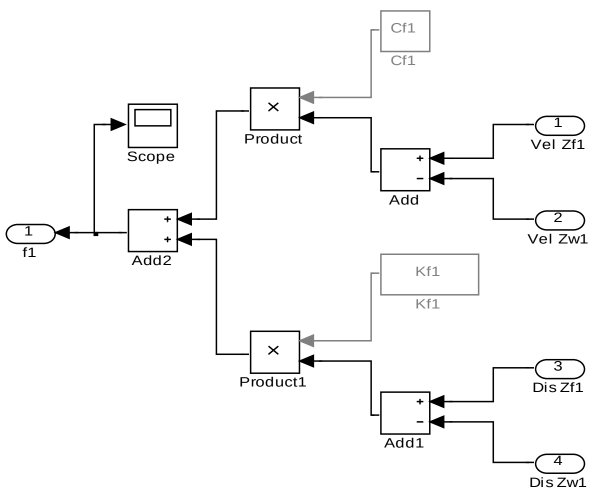


Figure 17 The subsystem that represents the springs and dampers parameters

Other than the longitudinal motion subsystem, there are also subsystems for pitch motion (for front bogie, rear bogie and body). These subsystems also have the same structure and are shown as diagram below;

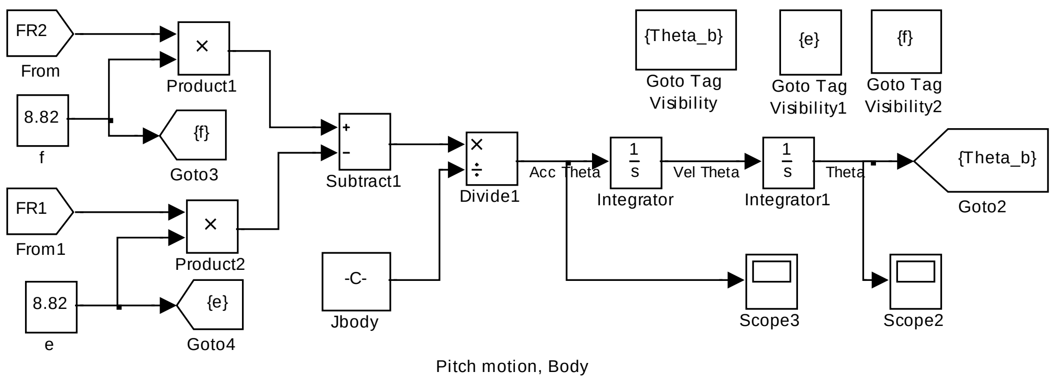


Figure 18 The subsystem structure for Pitch Motion

The structures for longitudinal motion subsystem are link with the structure for pitch motion subsystem using the “Go To” and “From” block diagrams.

Besides that, there are also input that need to be develop. The input will represent the rail track condition. In this project, there are two option of road profile that had been used. One of the road profiles produce repeating sequence input like the sine wave and another one is step input. The road profile block diagrams are shown as diagram below;

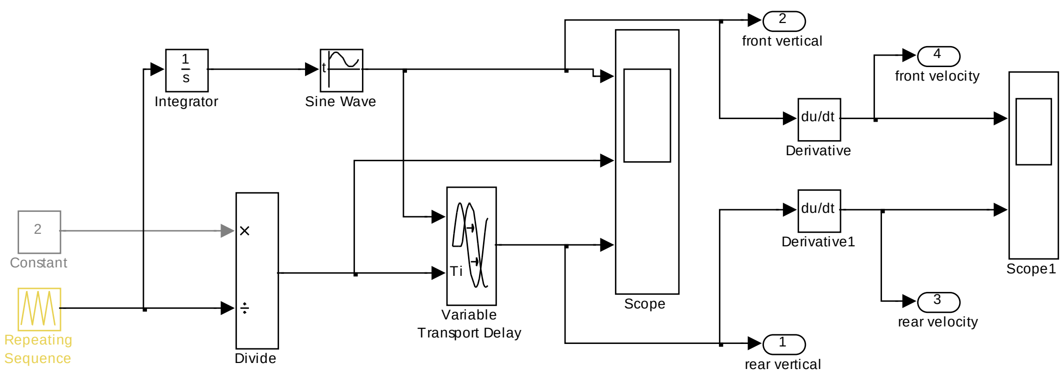


Figure 19 The road profile produce repeating sequence input

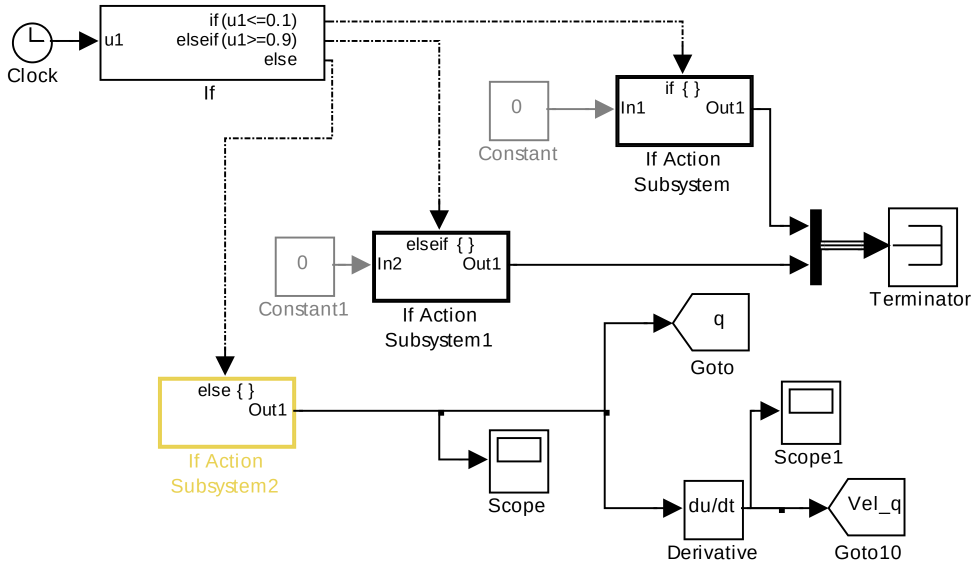


Figure 20 The road profile produce step input.

Before any simulation to be made, there is a requirement to put in the suspension parameter which is the value of the spring and damper. The parameter that involve in this simulation are as below;

Primary Suspension	Secondary Suspension
Spring = 975600 N/m Damper = 9910 N/ms	Spring = 530000 N/m Damper = 15000 N/ms
Bogie Mass = 3020 kg	Train Mass = 43200 kg

Table 1 Suspension Parameter

4.4 SIMULATION RESPONSE

This section will discuss on the response produce from the simulation of the train suspension block diagrams that had been shown in the previous section.

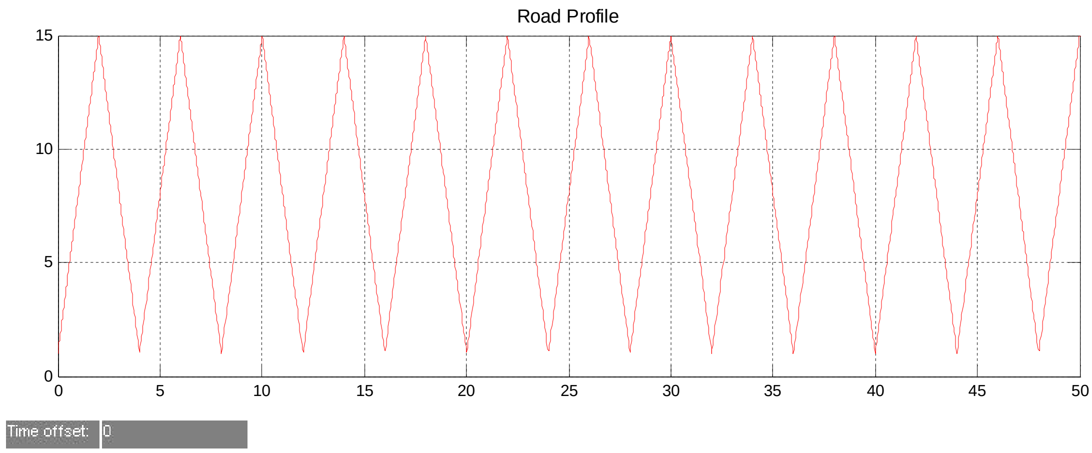


Figure 21 Road Profile – Repeating Sequence

Figure 19 show the road profile of repeating sequence. This type of road profile represents the condition of rail track that have bumpy condition where a gap exist between the rail connections. This kind of input has produce response that can be seen as diagram below (for body, front bogie and rear bogie);

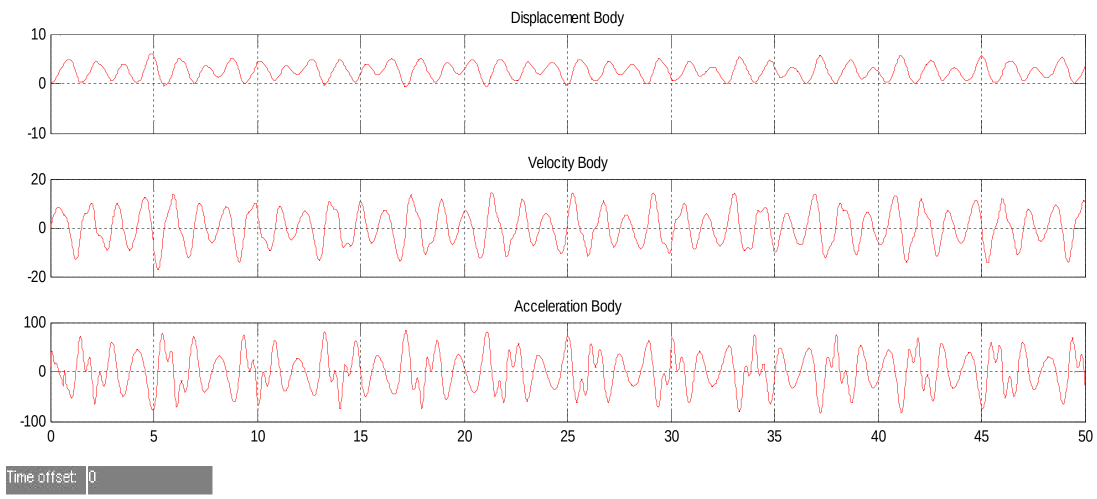


Figure 22 Responses for Longitudinal Motion for Body Train

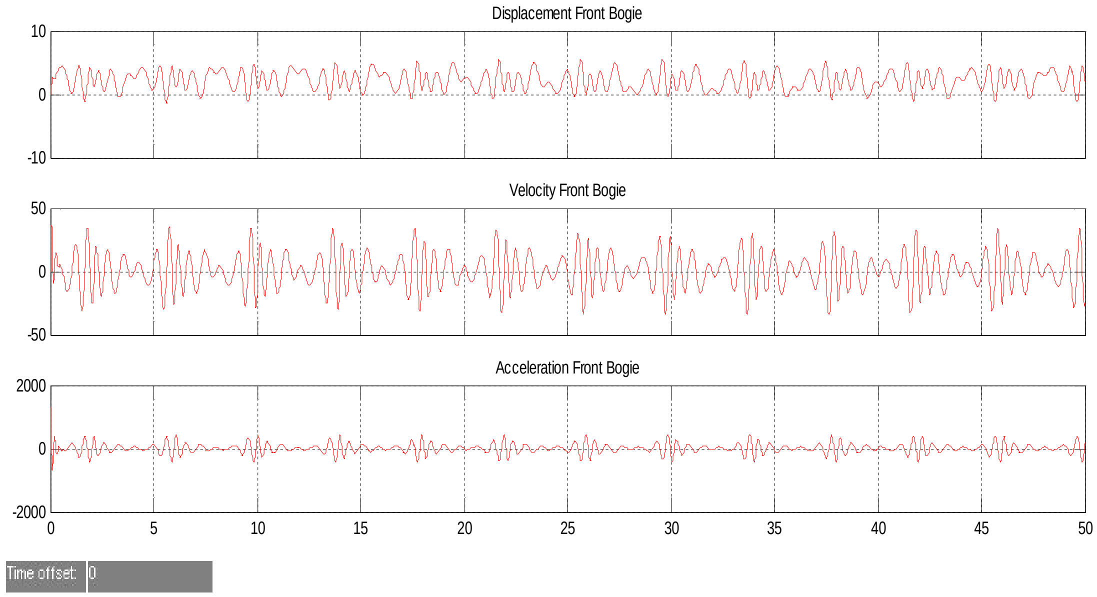


Figure 23 Responses for Longitudinal Motion for Front Bogie

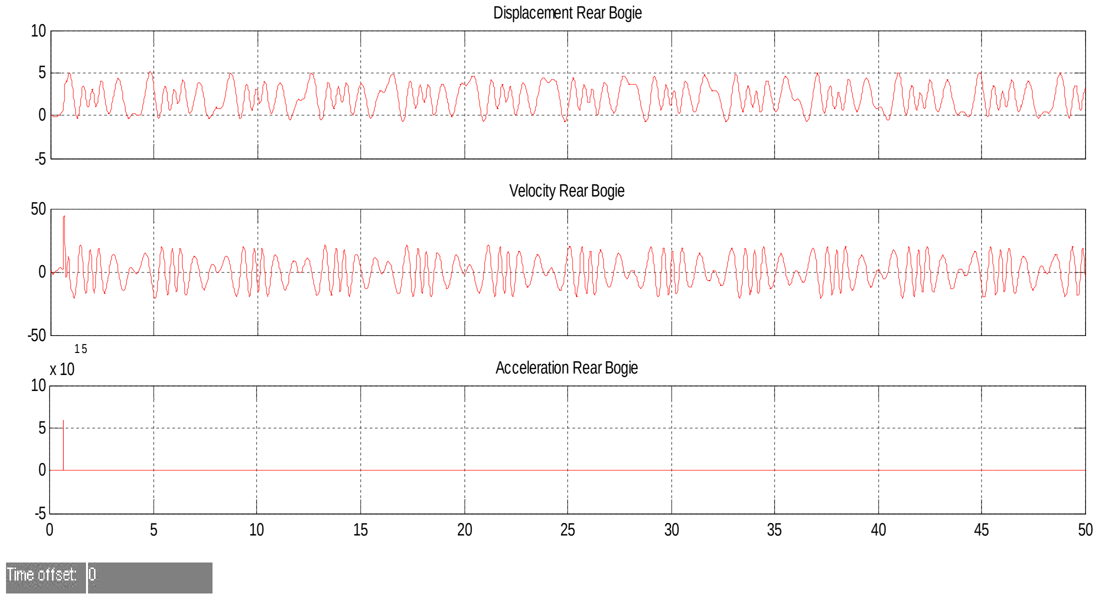


Figure 24 Responses for Longitudinal Motion for Rear Bogie

If we compare between the longitudinal response of the train body and both of the front and rear bogie, we can clearly see that the oscillation are much less. This can give a view that both primary and secondary suspensions are able to isolate most of the force load from the rail track.

The input from the road profile has an amplitude of displacement is 15mm and from the response, we can see that the amplitude of displacement for train body, front and rear bogie have only displacement amplitude less than 10mm. The response amplitude is less than the input which here has proof that the suspension can isolate amplitude of more than 5mm

Here we can say that, for further development of suspension system, it need to able to isolate vibration of more than 10mm which in this case could eliminate most of the load from the rail track.

In the response for pitch motion, the response for body, front bogie and rear bogie are shown as below;

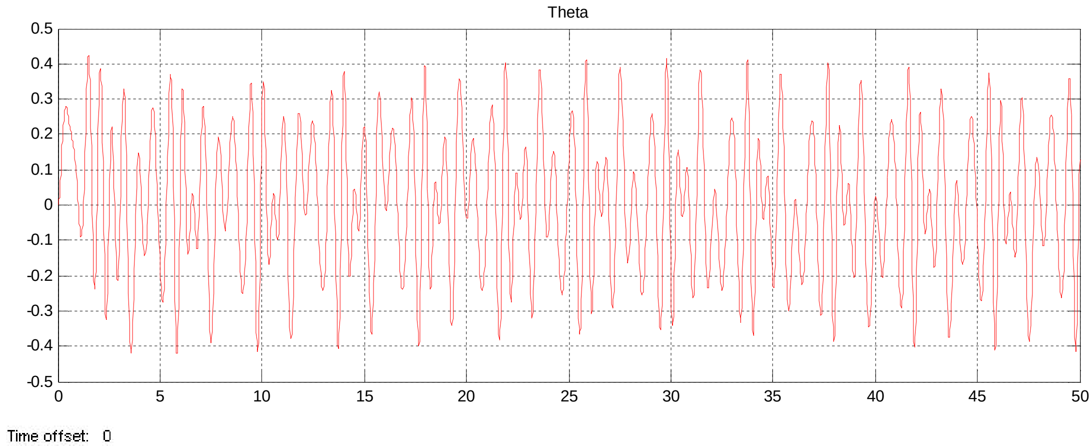


Figure 25 Response for Pitch Motion for Body Train

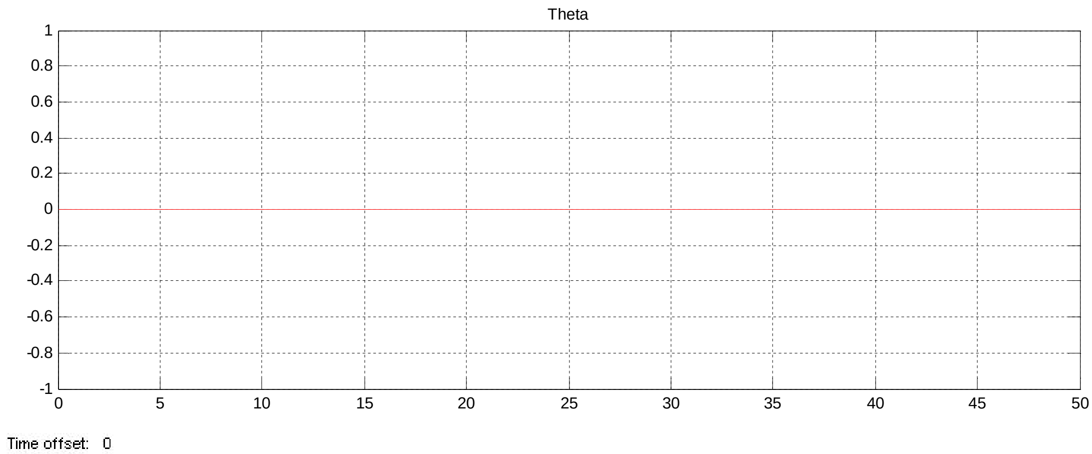


Figure 26 Response for Pitch Motion for Front Bogie

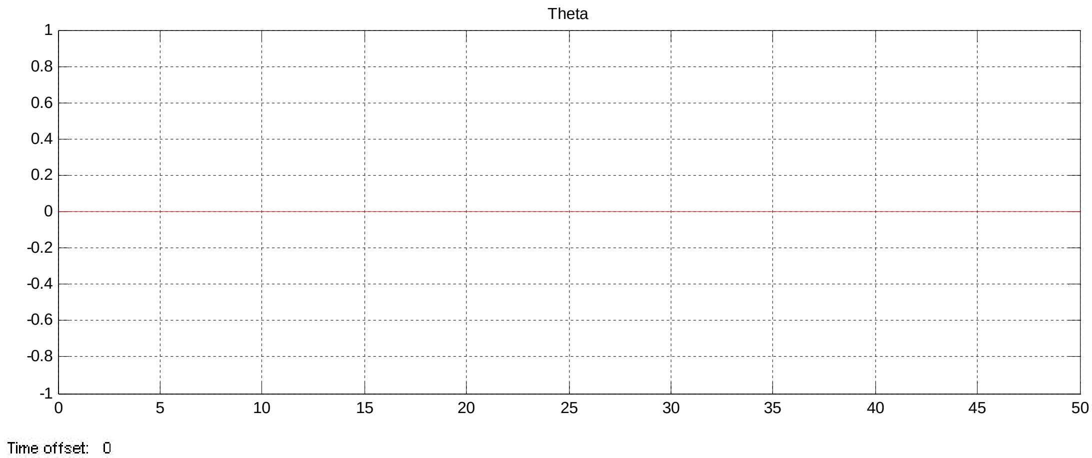


Figure 27 Response for Pitch Motion for Rear Bogie

Since load for both wheel for front and rear bogie are the same, the response is zero as the result. No pitch motion for both the front and rear bogie. But still, it does not affect the pitch motion response for train body. The average amplitude for pitch motion is about 0.3mm.

Beside a repetition of load, there is also another type of input which is the step input. This input represents the condition of the rail track where the rails have different level of alignment. The input is shown as below;

Figure 28 Road Profile – Step Input

This input produce response of longitudinal motion (for body, front bogie, rear bogie) as figure below;

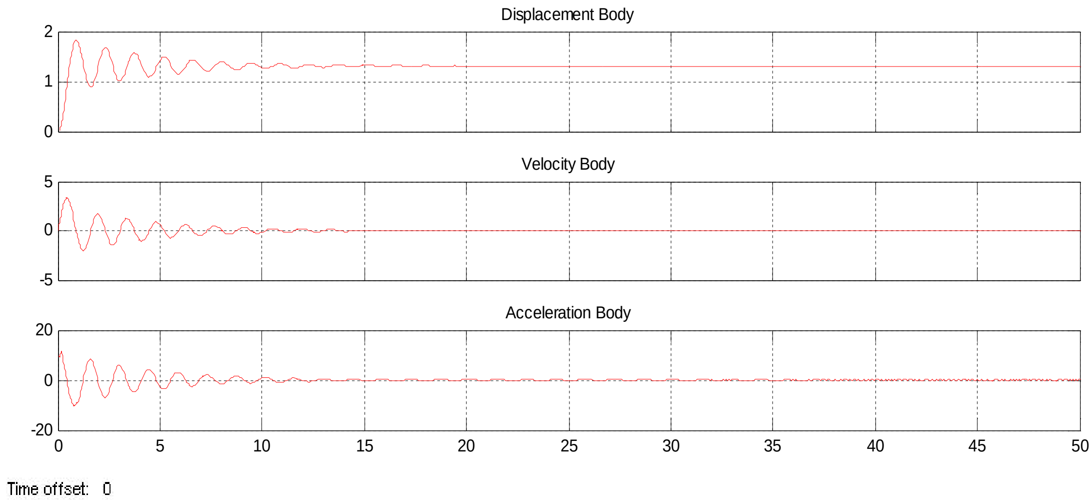


Figure 29 Response for Longitudinal Motion for Train Body

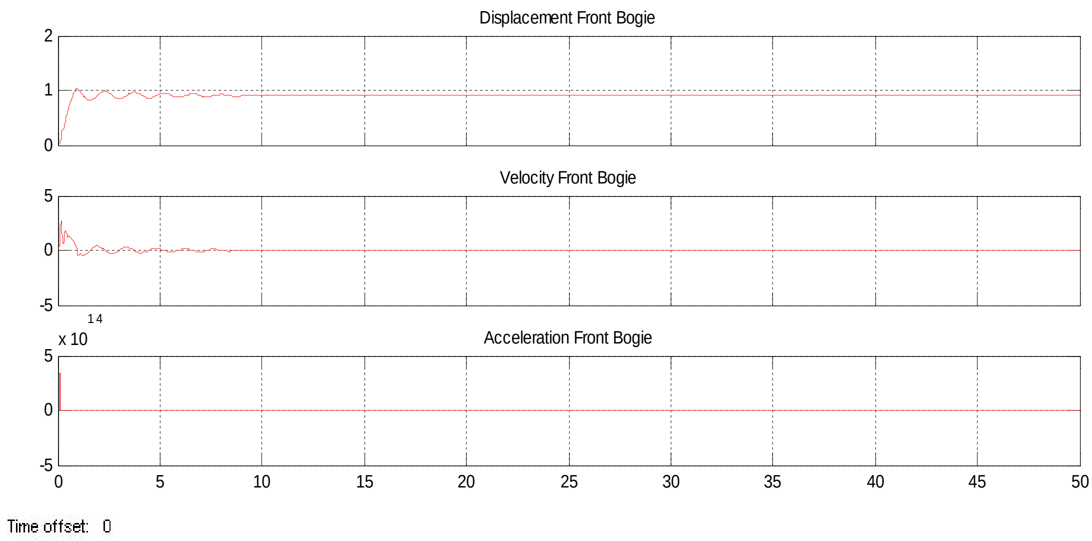


Figure 30 Response of Longitudinal Motion for Front Bogie

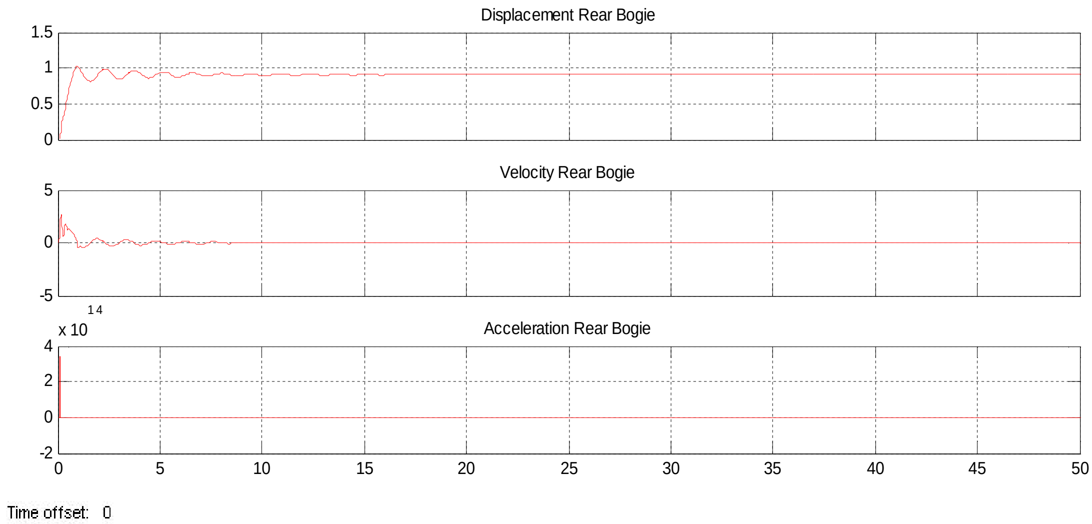


Figure 31 Response of Longitudinal Motion for Rear Bogie

Referring to the response for the train body, it can be see that the body moves to amplitude almost near to 2mm. the damping affect is then take response where it take about 20 seconds from the initial time for the train to settle down back to its initial position. Although the response show that the amplitude does not came back to zero, this does not meant it does not get back to its initial position. This affect is due to the increment of leveling from the rail track which is an increase of 0.8mm.

Front bogie needs time for about 10 second and 15 second for rear bogie. The amplitude after the damping effect shows that the bogie does not get back to its initial position. This might due to the increment of the rail track level and weight of the train body which might push the suspension and prevent the bogie from getting back to its initial position.

Below here, it is the response of pitch motion for body, front and rear bogie.

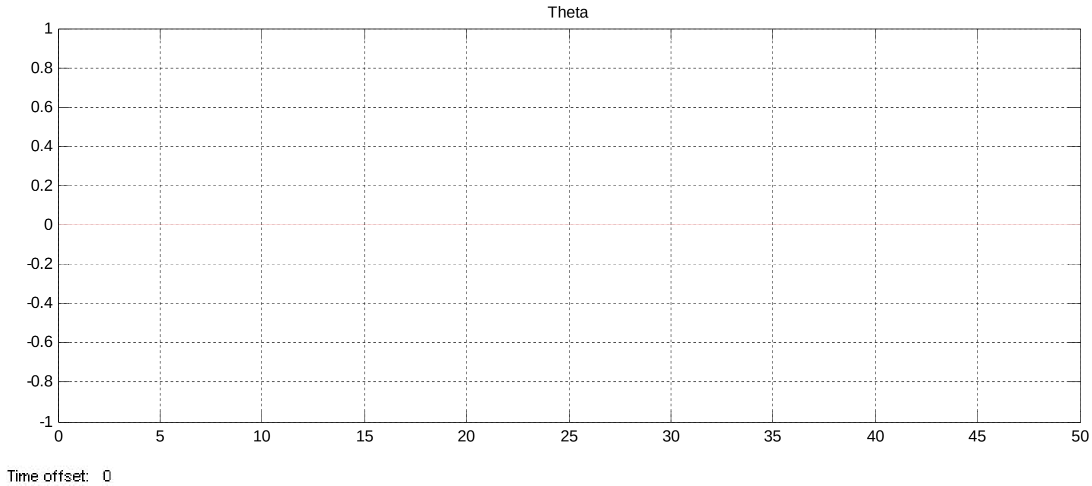


Figure 32 Response for Pitch Motion for Body, Front Bogie and Rear Bogie

The pitch motion response is likely to be the same as the pitch motion response from an input of repetition. This kind of response show us that the input does not affect the pitch motion for the train body, front and rear bogie with its related input.

Until here, we could see the response of the suspension due to the different type of input. Different input produces different response. The suspension parameter that been use in this simulation have been proof that it is able to isolate the load variance in 20 second. Generally, after receiving some input, the bounce frequency for the train body is about 0.6 Hz. This value is below the standard requirement for bouncing of passenger train which has a range between 0.9 Hz until 1.2 Hz [17].

SECTION 5
~ CONCLUSION & RECOMMENDATION~

5.1 CONCLUSION

After gone through this project, it can be seen that the simulation model built using MATLAB SIMULINK software is capable in simulating the condition of the train suspension system. Studies that were made had lead to the basic concept in vibration and suspension system and assist in build up the simulation model. Running the simulation had showed us the displacement, velocity and acceleration for train body, front bogie and rear bogie with the assumption that the train is symmetry and it able this project to only use half model of the train for simulation.

Only just by entering suspension parameters inside the simulation model, the motion of the train body, front bogie and rear bogie could be determine. This can help in determine which parameters have the optimal performance. This could help engineers and researcher in improving the current passenger train suspension system for a better ride quality.

5.2 RECOMMENDATION

Completing this project is a success but yet, there are still lots of room for improvement as the biggest room in the world is the room of improvement. This project is only considering the effect of suspension toward the longitudinal motion and pitch motion only. Thus, it is recommended that others motion such as lateral, rolling, yawing and etc motion could be include in the simulation. Other than this, it is also recommended to include the effect of the train motion in cornering as the effect contribute in the ride quality of the passenger.

REFERENCES

A. References that related to this project. Referring to the literature review section.

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[2] Niahn-Chung Shieh, Chung-Liang Lin, Yu-Chen Lin, Kuo-Zhoo Liang, 2005, "Optimal design for passive suspension of a light rail vehicle using constrained multiobjective evolutionary search", Journal of Sound and Vibration.

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[6] Anna Orlova Yuri Boronenko, 2006, "The Anatomy of Railway Vehicle Running Gear" in *Common Passenger Vehicle Bogie Design*, Part III, Page 65, Taylor & Francis Group, LLC.

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[15] Josepoh C. Musto ; William E. Howard ; Richard R. Williams, 2009, “Engineering Computations, An Introduction Using MATLAB and EXCEL” in *MATLAB Fundamentals,* Page 63, McGraw Hill, New York.

[16] Arun Rajagopalan and Gregory Washington, 2002, “SIMULINK Tutorial” in *Concept of Signal and Logic Flow,* Page 4, The Ohio-State University.

[17] Simon Iwnicki, 2006, “Handbook of Railway Vehicle Dynamics” in *The Anatomy of Railway Vehicle Running Gear*, Page 75, Taylor & Francis Group, New York.

B. Other related references;

1. Vigneswaran A/L M Ratnam, 2008, “Computer Simulation of Passive and Active Suspension System Using SIMULINK”, UniMaP.
2. James B. Dabney ; Thomas L. Harman, 1998, “Mastering SIMULINK 2”, Prentice Hall, New Jersey.
3. Josepoh C. Musto ; William E. Howard ; Richard R. Williams, 2009, “Engineering Computations, An Introduction Using MATLAB and EXCEL” in *MATLAB Fundamentals,* Page 63, McGraw Hill, New York.
4. Arun Rajagopalan and Gregory Washington, 2002, “SIMULINK Tutorial” in *Concept of Signal and Logic Flow,* Page 4, The Ohio-State University.
5. Rejeb H., Affiz Z., Bettaeib H., “Optimization of the design variables of rail vehicle system in rectilinear motion, Tunisia.

APPENDICES

Appendix A: Scan from “Computer-Aided Simulation In Railway Dynamins”, author: Rao V. Dukkipati & Joseph R. Amyot, 1988.

INTRODUCTION 9

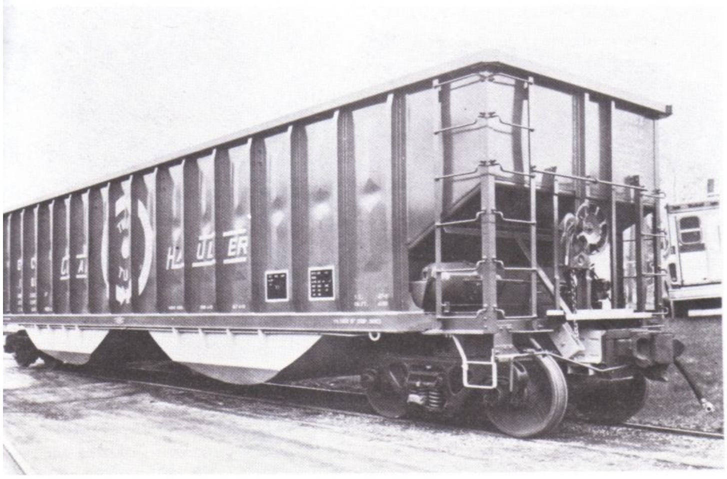


Fig. 1.4 Twin-tub coal hauler developed by the Greenville Steel Car Company. (Reproduced from Ellsworth et al. [3] with the permission of Greenville Steel Car Company.)

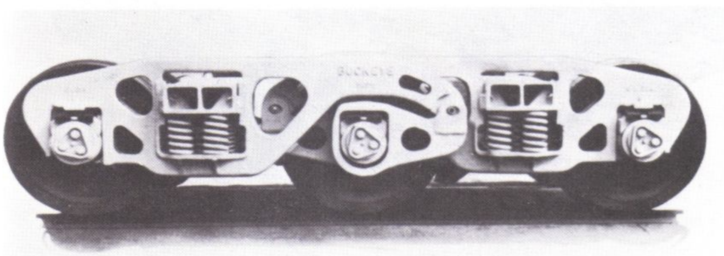


Fig. 1.5 Buckeye six-wheel elasto-cushion truck. (Reproduced from Ellsworth et al. [3] with the permission of Buckeye Steel Castings.)

Appendix B: Sample of MATLAB SIMULINK Tutorial.

Example 2. Mass-Spring-Dashpot System Simulation

Consider a mass-spring-dashpot system where the spring and the dashpot are connected in parallel to the mass. The mathematical model for this system is described by (2)

In this example I will illustrate how to use Simulink to simulate the response of this system to unit step input.

STEP 1

In Simulink, create a new model window (CTRL+N) and drag the following blocks from the Simulink library window:

Blocks to be dragged	Location in Simulink library browser
Step	Sources
Gain	Math Operation
Sum	Math Operation
Integrator	Continuous
Scope	Sinks
To Workspace	Sinks

STEP 2

By re-arranging Eqn 2 to yield an expression for the acceleration term, Eqn (2) Becomes

$$\ddot{x} = \frac{1}{m}\left(f(t) - c\dot{x} - kx\right) \qquad (3)$$

Based on Eqn 3, we connect the blocks in the diagram as shown in Figure E2-2. Use CTRL+F and CTRL+R to flip and rotate the blocks as necessary (select the block first then execute the key sequence). Note that you can use CTRL+right mouse button to create branches of the connecting lines. Don't worry about the parameter values and the signs for these blocks at this point as we'll take care of this in STEP 3. Just get them connected first.

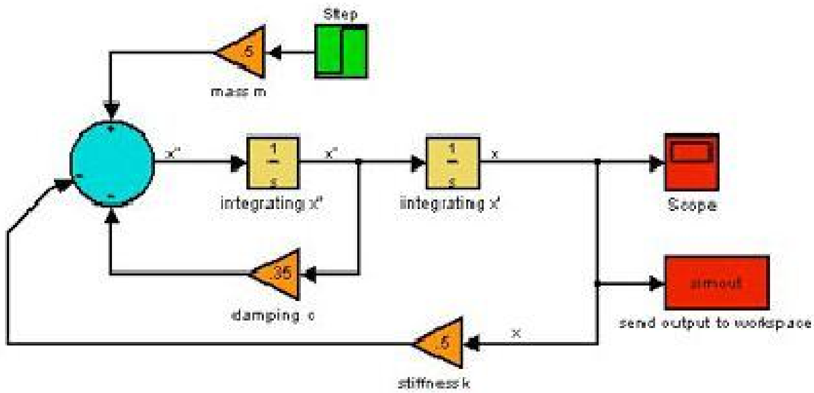


Figure E2-2

STEP 3

Enter the values of the parameters for each block. In this example, we will set m = 2.0; c=0.7; k=1. You are encouraged to try different values and observe the system's response to step input.

To show that you may obtain different form of output, I included another block (in addition to the scope block) called "simout". This block can be found in the Sinks group from the Simulink Library browser. The output from this block is used in Matlab workspace. To illustrate how this block works, I will select a name for the output called "simout" as the variable name in the block's parameter setting (double click on the "simput" block to bring up the parameter dialog window). In additon, I will need a time array from the simulation. This can be specifed as a parameter in the Simulation Parameter window (CTRL+E) under the Workspace I/O tab as shown in Figure E2-3.

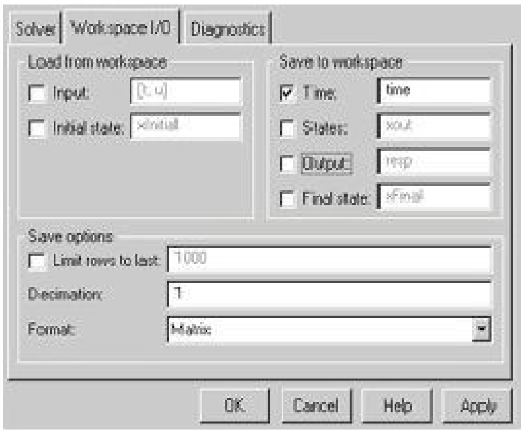


Figure E2-3

STEP 4

Run the simulation by clicking on the button (alternately you may use keyboard command CTRL+T). The screenshot of the output from the Scope block is show in Figure E2-3.

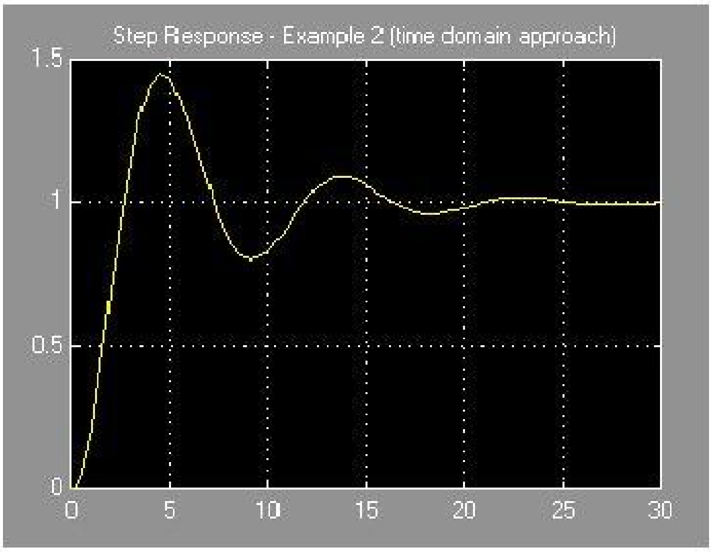


Figure E2-3

That's it! You have successfully modeled and simulated a second-order underdamped dynamic system. To exam different responses, feel free to change different values for *m*, *c*, and *k* in the gain blocks. To see how you can use the output from the "simout" block (by the way, you may name the block whatever you wish), go to Matlab Command window and type

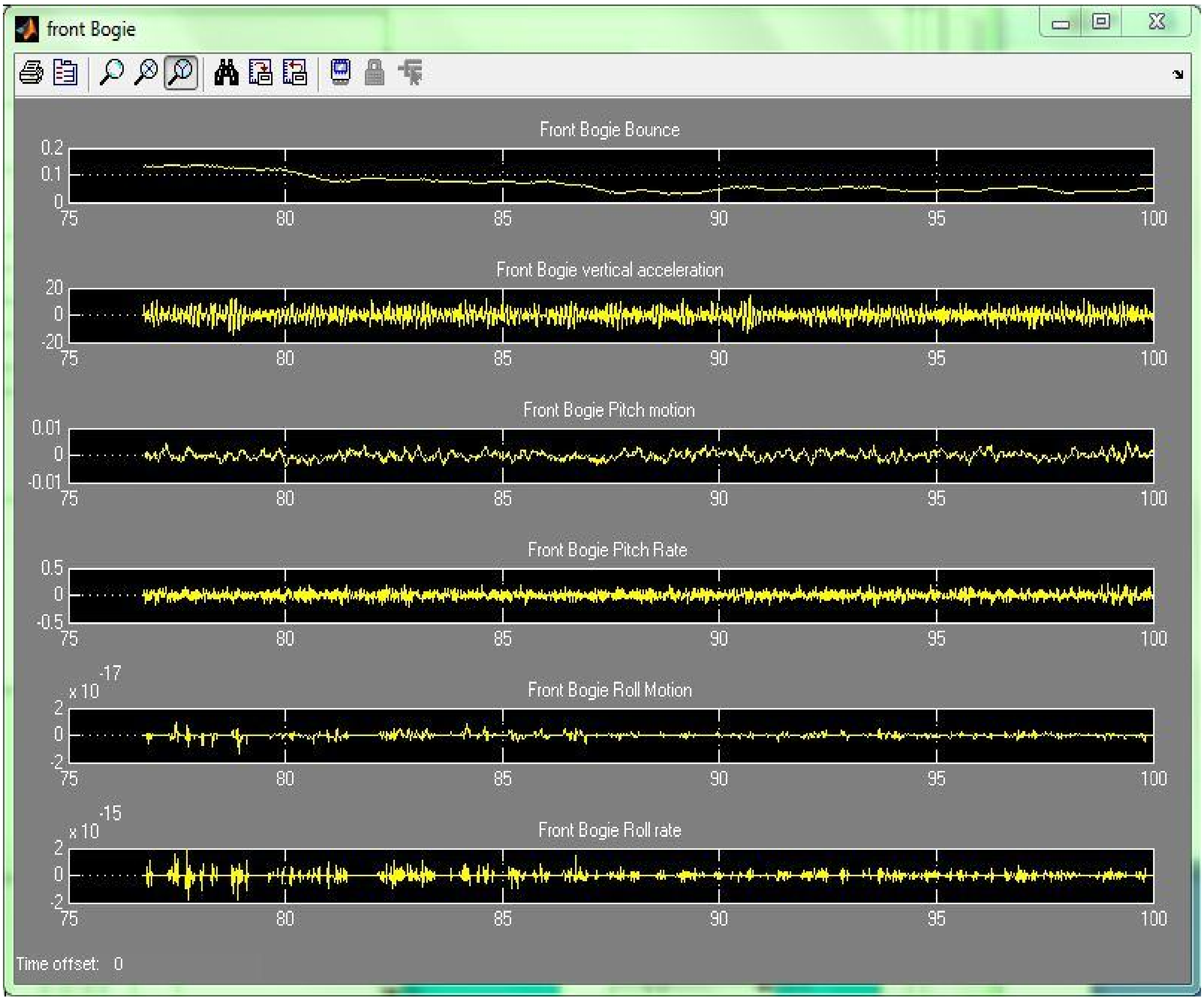
>> **who**

You should receive an echo from Matlab listing the following variables: "simout" and "time" (and perhaps others variables in the current workspace memory). Now, you may create a plot of the system response identical to that shown in the Scope output. The command for creating this plot is:

>>**plot(time,simout);grid**

Note that the output format used in the example above is *matrix* type. The output sent to workspace can be used for further analysis and storage in ascii format. Output to workspace allows more options in plot presentation and further data analysis as the arrays are in ascii format.

Appendix C: Result on Example of Full Simulation. Source: MATLAB training website.



Appendix D: Result on Basic model of mass-spring-damper simulation