ACTIVE SUSPENSION SYSTEM DESIGN FOR RAILWAY VEHICLES TRANSPORTING SENSITIVE GOODS AND HAZARDOUS MATERIALS

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ABSTRACT

This project presents the dynamic modelling and control of railway vehicle active suspension systems. The vehicle types selected for this study are the two-axle and bogie-based railway vehicle. The performances of the passive and active suspensions are simulated and compared as the vehicle moves on straight and curved track. The input to the system is the curve radius and its corresponding cant angle. The curving performance was evaluated from the lateral and yaw displacement of the wheelset, bogie and vehicle body. The wheelset arrangement for active suspension selected in this study is the actively-stabilized wheelset with rotary actuator and the wheelset with independently- rotating wheels. The optimal controller was chosen to control the lateral and yaw deflections of the vehicle. The comparison between the two-axle (without bogie) and bogie-based vehicles, as well as the active suspension with actively stabilized wheelset and independently rotating wheels are illustrated to highlight the advantages and disadvantages of each vehicle type and active suspension options. The active suspension of railway vehicle with independent rotating wheelset showed a better curving performance than the one with solid axle wheelset as the wheels were no longer connected to each other.

ABSTRAK

Projek ini membincangkan model dinamik dan sistem kawalan bagi suspensi aktif keretapi. Jenis keretapi yang dipilih dalam projek ini ialah keretapi bergandar dua (*two-axle*) dan keretapi berserta 'bogie'(*bogie-based*). Hasil prestasi bagi suspensi pasif and aktif disimulasikan dan dibandingkan sewaktu keretapi bergerak di atas landasan lurus dan berselekoh. Masukan bagi sistem ini merupakan jejari selekoh and darjah kecondongan selekoh. Hasil prestasi sewaktu selekoh diukur daripada anjakan secara melintang (lateral) and rewang (yaw) bagi set roda, 'bogie' dan badan keretapi. Susunan set roda bagi suspensi aktif yang dipilih dalam projek ini ialah set roda yang distabilkan secara aktif dengan pendorong berputar dan set roda dengan roda yang berputar secara bebas. Pengawal optimum dipilih untuk mengawal anjakan melintang dan rewang bagi keretapi tersebut. Perbandingan di antara keretapi bergandar dua dan keretapi berserta 'bogie' dan sistem suspensi aktif dengan set roda yang distabilkan secara aktif dan set roda dengan roda yang berputar secara bebas dibuat untuk menjelaskan kelebihan dan kekurangan setiap jenis keretapi dan pilihan suspensi aktif. Suspensi aktif bagi keretapi yang menggunakan set roda dengan roda yang berputar secara bebas menunjukkan prestasi sewaktu selekoh yang lebih baik daripada keretapi yang menggunakan set roda dengan pendorong berputar.

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LIST OF SYMBOLS

A_a, B_a, C_a, D_a - State, input, output and feedforward matrices of the two-axle railway vehicle state-space equation

A_b, B_b, C_b, D_b - State, input, output and feedforward matrices of the bogie-based railway vehicle state-space equation

$A_{IRW}, B_{IRW}, C_{IRW}, D_{IRW}$ - State, input, output and feedforward matrices of the independent rotating wheels railway vehicle state-space equation

A_w, B_w, C_w, D_w - State, input, output and feedforward matrices of the wheelset System state-space equation

C_m - Controllability matrix

C_s, K_s - Secondary lateral damping and stiffness per wheelset

C_w, K_w - Primary lateral damping and stiffness per wheelset

C_y, K_y - Secondary yaw damping and stiffness per wheelset

CD - Cant deficiency

F_y - Lateral force applied to the wheelset

f_{11}, f_{22} - Longitudinal and lateral creep coefficients

G_a - Disturbance matrix of the two-axle railway vehicle state-space equation

G_b - Disturbance matrix of the bogie-based railway vehicle state-space equation

G_{IRW} - Disturbance matrix of the independent rotating wheels railway vehicle state-space equation

g - Gravitational acceleration

g_r - Rail gauge

I_b - Bogie moment of inertia

I_{rw} - Wheel rotational inertia

I_v	- Vehicle body moment of inertia
I_w	- Wheelset moment of inertia
K	- Feedback gain matrix
l	- Half gauge of wheelset
l_b	- Half spacing between two wheelset
l_v	- Half spacing between two bogies
m	- Mass of the wheelset
m_b	- Mass of the bogie
m_v	- Mass of the vehicle body
O_m	- Observability matrix
$P_r(t)$	- Solution of the Ricatti equation
Q, R	- Weighting matrices for the minimization of LQR cost function
R	- Radius of the track curvature
R_1, R_2,	- Radius of the track curvature at leading and trailing wheelsets for front bogie
R_3, R_4	- Radius of the track curvature at leading and trailing wheelsets for rear bogie
r	- Wheel radius
SE	- Superelevation of the track
T_ψ	- Yaw torque applied to the wheelset
$T_{\psi 1}$, $T_{\psi 2}$	- Yaw torque applied to the leading and trailing wheelsets (front bogie)
$T_{\psi 3}$, $T_{\psi 4}$	- Yaw torque applied to the leading and trailing wheelsets (rear bogie)
u	- System input
V	- Vehicle speed
V_{bal}	- Vehicle balance speed on curved track
w	- Deterministic track input
y_{b1}, y_{b2}	- Front and rear bogie's lateral displacement
$\dot{y}_{b1}, \dot{y}_{b2}$	First order derivative of front and rear bogie's lateral displacement
y_v	- Vehicle body's lateral displacement
$\dot{y}_v$	- First order derivative of vehicle body's lateral displacement

y_w	- Wheelset lateral displacement
y_{w1}, y_{w2}	- Leading and trailing wheelsets' lateral displacement (front bogie)
y_{w3}, y_{w4}	- Leading and trailing wheelsets' lateral displacement (rear bogie)
$\dot{y}_{w1}, \dot{y}_{w2}$	- First order derivative of respective wheelsets lateral displacement (front bogie)
$\dot{y}_{w3}, \dot{y}_{w4}$	- First order derivative of respective wheelsets lateral displacement (rear bogie)
λ	- Conicity
ψ_w	- Wheelset's yaw displacement
ψ_{w1}, ψ_{w2}	- Leading and trailing wheelsets' yaw displacement (front bogie)
ψ_{w3}, ψ_{w4}	- Leading and trailing wheelsets' yaw displacement (rear bogie)
$\dot{\psi}_{w1}, \dot{\psi}_{w2}$	- First order derivative of respective wheelsets yaw displacement (front bogie)
$\dot{\psi}_{w3}, \dot{\psi}_{w4}$	- First order derivative of respective wheelsets yaw displacement (rear bogie)
θ_c	- Cant angle of the track curvature
θ_{c1}, θ_{c2}	- Cant angle of the curved track at the leading and trailing wheelsets (front bogie)
θ_{c3}, θ_{c4}	- Cant angle of the curved track at the leading and trailing wheelsets (rear bogie)
ϕ_{w1}	- Relative rotational angle between two wheels (leading wheelset)
ϕ_{w2}	- Relative rotational angle between two wheels (trailing wheelset)
$\dot{\phi}_{w1}$	- First order derivative of relative rotational angle between two wheels (leading wheelset)
$\dot{\phi}_{w2}$	- First order derivative of relative rotational angle between two wheels (trailing wheelset)

LIST OF ABBREVIATIONS

AAP	-	American Association of Railroads
IRW	-	Independently-Rotating Wheels
KTMB	-	Keretapi Tanah Melayu Berhad

CHAPTER 1

INTRODUCTION

1.1 Introduction to Railway Vehicle Suspension System

Railway vehicle consists of vehicle body, bogies and wheelsets connected via a particular suspension arrangement. As can be seen in Figure 1.1, a railway coach has a body at the uppermost of the arrangement. Under the vehicle's body, there are two bogies which are connected to the body via suspension. This suspension is also known as secondary suspension. For each bogie, there are two wheelsets placed in parallel with each other under the bogie. The wheelsets are attached to the bogie through another set of suspension called primary suspension.

Primary suspension is applied for the purposes of running stability (critical speed), curving performance and supporting the vehicle's weight. On the other hand, secondary suspension is important to ensure a good quality ride and provide safe conditions of the transported goods by reducing the vibrations due to track irregularities.

Each of the vehicle components has its own reason of presence. Vehicle body provides spaces for transported goods as well as for passengers. On the other hand, bogies are applied in the system to guide or steer the vehicle along the course of the track and to isolate the vehicle and its payload from unintended imperfections in the position of the track [1].

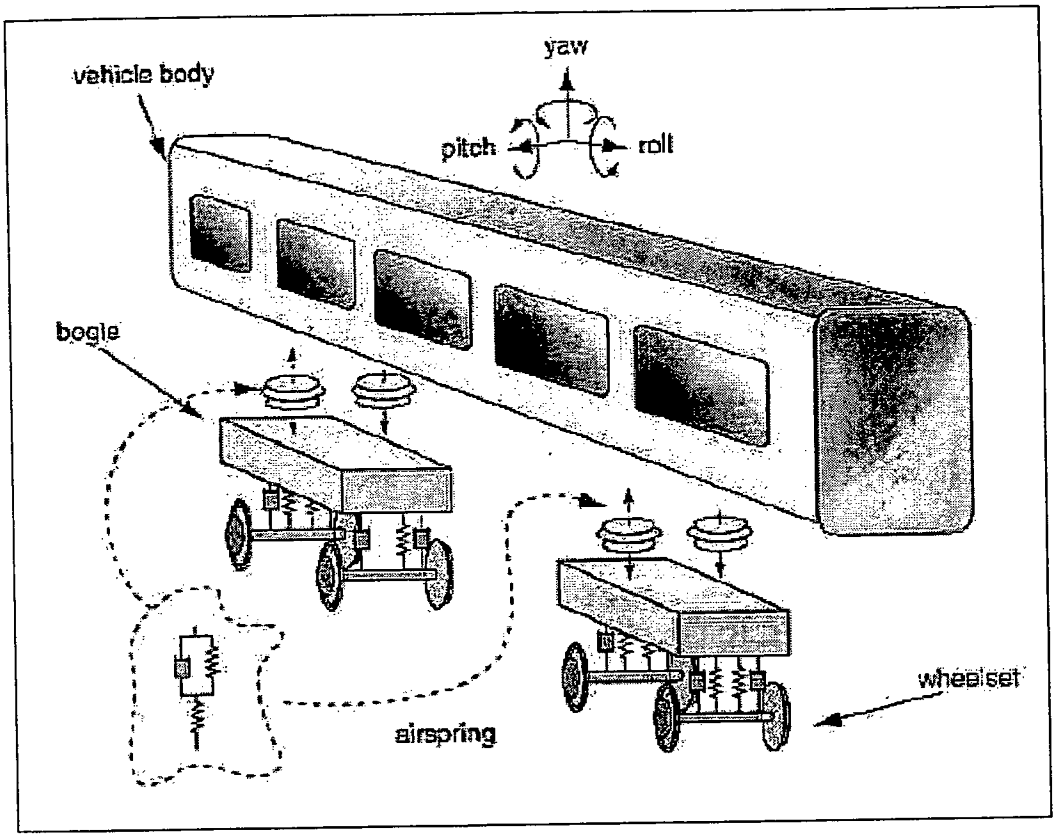


Figure 1.1: Railway vehicle suspension arrangement

1.2 Introduction to Sensitive Goods and Hazardous Materials

Hazardous materials can be explosive, flammable, toxic, radioactive, corrosive or harmful in some ways or another to humans, animals and the environment. These materials need to be transported safely to avoid any physical damage to their surroundings. The empty containers and packages of dangerous goods can present the same hazards as the chemical substance or product they contained and should also be regarded as dangerous goods.

Sensitive goods are used to represent materials or goods which are fragile and weak against any presence of disturbances and vibrations. Any mishandling can cause those goods to damage or at least fail to function correctly and thus result in economical losses. Even though sensitive goods damages do not cause any major destruction as bad as hazardous materials do to the surroundings but failure to protect those goods can become a great loss to industries if accidents happen.

Industrial production takes place, and raw materials are located, all over the world. Several options of transportations are available to move the materials between two or more destinations such as by using airplanes, ships, road vehicles and railway vehicles. The main issues in choosing the vehicle type to transport goods between places are time consumption, cost, and security of the goods against damages.

Railroads provide the most cost efficient and clean forms of land transportation [2] of sensitive goods and hazardous materials. Besides that, there are some other advantages of using railway vehicles to transport materials via land. The advantages are trains are fuel-efficient, produce less greenhouse gasses and provide resource conservation [3]. The transportation and storage of dangerous chemicals and goods have to be improved to ensure the safety of the goods along the journey.

Railway vehicle plays an important role to transport such hazardous materials between the location of raw materials to industrial production places and from the manufacturing location to customers. Sensitive goods carried via railway vehicle depend mostly on the suspension system of the vehicle to overcome the effects and vibrations produced when track irregularities are met.

According to United Nations statistics, it is shown that half of all goods transported belong to the category of dangerous goods. For example, eight-five percent of chlorine, which is one of the very dangerous chemicals, is transported by rail [4]. Large amounts of other highly dangerous goods, such as hydrochloric acid, sulphuric acid, sulphuric dioxide, nitric acid, phenol and methanol are transported regularly.

1.3 Background of the Problem

The most important component in a railway vehicle system is its wheelset. The wheelset consists of two coned (or otherwise profiled) shape wheels connected by an axle. The inner side of the wheels has a larger radius wheel flange compared to the outer side. Figure 1.2 shows the features of a railway solid-axle wheelset.

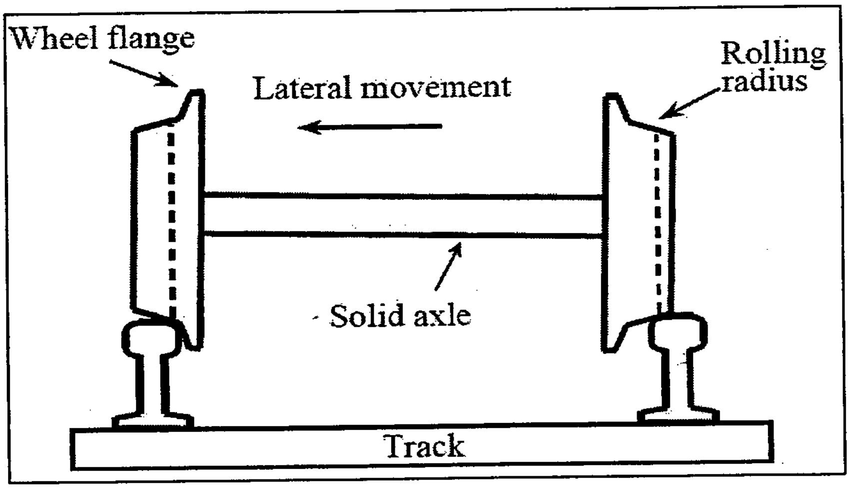
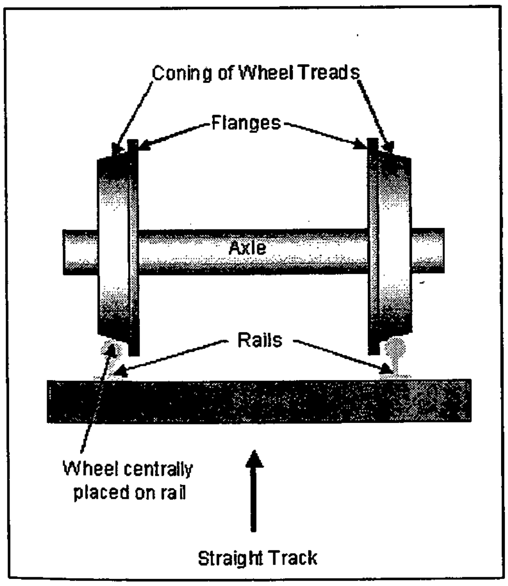


Figure 1.2: Solid-axle railway wheelset features.

1.3.1 Wheelset Dynamics

It is essential to understand how the conventional railway wheelset works before any possible implementation of active elements can be applied to improve the system and thus, overcome the limitations of mechanical suspension. For further explanation in this section, only the solid-axle wheelset dynamics is discussed.

On straight track, the wheelset runs in a centralized position as shown in Figure 1.3(a). When the vehicle wheelset encounters a curve, it naturally moves outwards. The side by side wheels connected by an axle run on different radius at that moment. The outer wheel runs on a larger radius but the inner wheel moves with a smaller radius as can be seen in Figure 1.3(b). Both wheels have to rotate at the same rotational speed, thus the outer wheel moves faster along the track. In design purpose, it is important to make sure there is no contact between the wheel flange and the rail to avoid large amount of wear on the wheels and rails and to reduce noise [5].



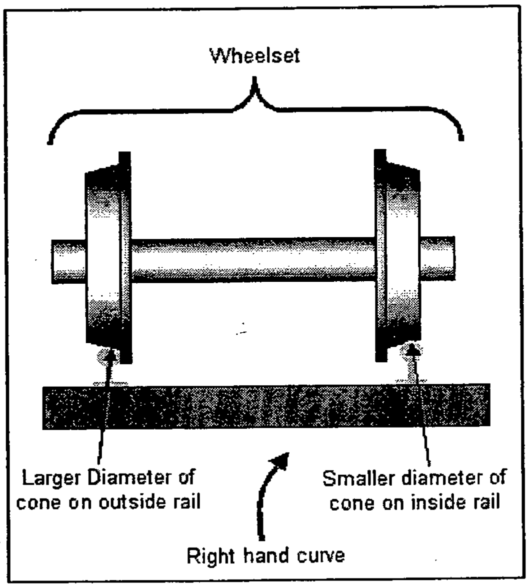


Figure 1.3(a): Wheelset on straight track. Figure 1.3(b): Wheelset on curved track

In general, the lateral and yaw displacement of a single wheelset are depending on creep damping and creep stiffness of the wheelset. Due to the lateral displacement, the wheelset interactions with the rails can cause damages to the track, wear of rails, wear of wheel flange, and noise in the contact area [6].

For a single wheelset, the second-order differential equations that represent the relationship of creep damping and creep stiffness coefficient with lateral and yaw displacement can been shown below:

$$\ddot{y} = \frac{-2f_{11}}{mV}\dot{y} + \frac{2f_{22}}{m}\psi + \frac{1}{m}F_y \quad (1.1)$$

$$\ddot{\psi} = \frac{-2f_{11}l\lambda}{I_w r}y - \frac{2f_{11}l^2}{I_w V}\dot{\psi} + \frac{1}{I_w}T_\psi \quad (1.2)$$

where; y is the lateral displacement of the wheelset

ψ is the yaw angle (angle of attack)

F_y is the external lateral force

T_ψ is the external yaw torque

m is the mass of the wheelset

I_w is the moment of inertia of the wheelset

f_{11} is the longitudinal creep coefficient of the wheelset

f_{22} is the lateral creep coefficient of the wheelset

1.3.2 Problem with Passive Suspension

As previously mentioned, primary suspension system mainly deals with the stability of the vehicle while secondary suspension provides good quality ride. For a railway vehicle, it is vital to design suspension systems that are capable of handling both objectives. Since the earlier age of railway vehicle, conventional suspension system which is also popularly known as passive suspension only comprises of mechanical elements [7].

Passive suspension system is a traditional suspension that utilizes passive components inside a railway vehicle's suspension system. These conventional passive components consist of coil or leaf springs, viscous dampers and several mechanical parts [8], such as linkages to support the vehicle mass and the load carried inside the vehicle body.

A passive suspension system has the ability to store energy via springs and to dissipate energy via dampers [9]. Parameters of a primary passive suspension system are generally fixed and being chosen to achieve a certain level of compromise between running stability and curving performance. By using stiff springs, it will result in stable high-speed running but poor curving performance. On the other hand, soft springs show a better curving performance but stable running is not possible at high-speeds [10]. Figure 1.4(a) and Figure 1.4(b) illustrate the previously mentioned trade off issue between stiff and soft springs.

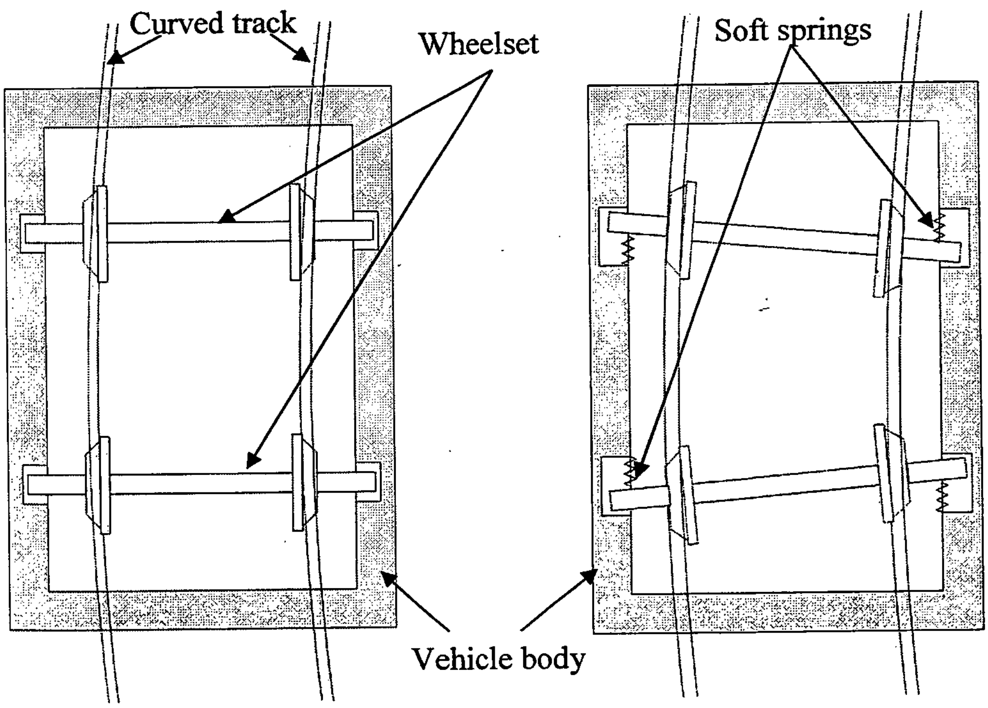


Figure 1.4(a): Stiff bogie design

Figure 1.4(b): Soft bogie design

Another issue that reveals the weaknesses of passive suspension system is related to secondary suspension. For a secondary suspension system whose main objective is to provide good quality ride for passenger train or to ensure the safety of carried sensitive goods and hazardous materials for freight train, the main obstacle is to deal with the vibration due to track vertical irregularities. It is difficult to design a passive suspension that can perform well [11]. The main reason is passive elements such as springs and dampers can only store or dissipate energy which is not possible enough to reduce the vibrations imposed on the vehicle body.

The secondary springs from bogie to the body are there to transmit the low frequency movements so that the vehicle follows the track and the isolate the higher frequency (due to irregularities). For dampers, the amount of damping is difficult to design because if it is too low there will be a lot activity in the resonant modes. On the other hand, if the damping is too high, the damper will transmit the movement to the vehicle body.

As a conclusion here, there are several limitations of passive suspension system which are vital but unavoidable especially when dealing with curves. Thus, it is necessary to find a better solution to improve the performance of suspension for railway vehicle.

1.3.3 Possibilities and Advantages of Active Suspension

Due to the limitations of passive suspension system, many researchers have focused on active suspension systems since the last 40 years [12]. Actually, the concept of an active suspension is to add actuators, a controller and sensors to an existing passive system [13]. The additional elements include actuators to apply force or torque, sensors to measure and sense variable changes and feedback controller to provide control commands for the actuators. This type of suspension also requires an external power source.

Active suspension can continually supply and modulate the flow of energy. Thus in active system, forces can be generated, and does not depend upon energy previously stored by the suspension via spring. An active system may also generate forces which are functions of many variables. Some of them may be remotely measured.

Active elements can be applied to both primary and secondary suspension. First, the potential active element to be applied on primary suspension system is discussed. As mentioned previously, a passive spring has fixed characteristic, either "stiff" or "soft" which causes in an extremely difficult to obtain a good performance when dealing with curves [14]. By replacing longitudinal springs with actuators, a better characteristic can be achieved which is not possible with a passive solution. In general, there are possibilities to place active elements in both directions to the bogie that can provide wider control approach choices.

Besides, active elements can also be implemented on secondary suspension. By applying actuators as additional elements in the secondary suspension, the actuators can increase the damping and thus controlling the resonance of the suspension without generating much vibration on the vehicle body [15].

Active suspension has many advantages compared to passive suspension system. As a summary, the potential advantages of such active suspensions are that they have low natural frequencies, which result in greater passenger comfort whilst still maintaining small static deflections, low dynamic deflections particularly under conditions of transient excitations, their suspension characteristics are maintained regardless of loading variations, high speed of response to any input and high flexibility in the choice of dynamic response especially different modes of the vehicle [16].

There are several high-speed passenger railway vehicles that have been developed. For example, the Shinkansen train in Japan began operating at 240 km/h since 40 years ago. Today, this train has the ability to travel at almost 300 km/h [17]. Bear in mind that a railway vehicle suspension system must have the capability of dealing the curves to ensure they can run in high speed. In this situation, active suspension is the best option to achieve that performance goal.

1.4 Objectives of the Project

1. To understand the active suspension system for railway vehicles.

   By having knowledge on suspension system for railway vehicle, the importance of active suspension to ensure the safety of carried hazardous material using railway vehicle is understood. Similarly, sensitive goods have several safety requirement needed to be achieved if those materials are to be transported via railway.

2. To build mathematical models for a bogie-based railway vehicle suspension system.

   For mathematical and calculation studies, the railway vehicle to be studied is limited to one carriage of the train that consists of one vehicle body, two bogies and four wheelsets. Generally, suspension system for railway vehicle is composed of springs, dampers and active elements. The only different between passive and active suspension system in term of components inside the system is the presence of active elements for active suspension system.

3. To design controllers for active primary suspension system.

   Based on the developed mathematical model, the controller to be designed will be selected from several options of modern control theory. In this study, linear quadratic regulator (LQR) is selected as the controller. The controller is applied to three types of wheelset arrangement; two-axle, bogie-based and independently rotating wheels (IRW) vehicles.

4. To simulate the linear model of the designed systems.

   The model and controllers developed are then simulated by using MATLAB software. The linearized model is to be considered in this simulation study. Several assumptions related to the model that is to be linearized will be stated. The performances of the passive and active suspensions are simulated to compare their advantages and limitations.

5. To analyze the controller performance.

   The controller performance is analyzed in terms of the lateral displacement and yaw angle of the wheelset, bogie and vehicle body, as well as the lateral acceleration of the body and the required torque to control the system during curving. The characteristics of each vehicle are compared and their advantages are distinguished.

1.5 Scope of the Project

Two types of vehicle are considered in this research. The first vehicle is called two-axle vehicle which consists of two wheelsets and a vehicle body. Each wheelset has a set of suspension elements which are spring, damper and rotary actuator (for active suspension only). The spring and damper are connected laterally at each side of the wheelset to the vehicle body. No spring presents in longitudinal direction of the wheelset. The second vehicle is called bogie-based vehicle. It has four wheelsets, two bogies and a vehicle body. As a contrast to the two-axle vehicle, the bogies are placed between the wheelsets and the body. Suspensions attached between the wheelset and bogie are called primary suspension while those between the bogie and body are known as secondary suspension.