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International Journal of Robotics and Mechatronics

Modeling a Small-Scale Test Rig of Quarter Car Railway Vehicle Suspension System

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***Abstract*—**Suspension system is a mechanism which isolates the vehicle body from road shocks and unwanted vibrations. A basic suspension system usually consists of spring, damper, rods, and ball joints in both automotive and railway transportation. The primary aim of this project is to design and develop a small-scale test rig of quarter car railway vehicle suspension system. This paper describes component selection strategy, technical design procedure, and research investigation of test rig and suspension system. The rig design and motion analysis is conducted by using Solidworks motion study tool where dynamic characteristic of the system, such as, required torque, acceleration and displacement of vehicle body and bogie are investigated based on selected parameters and track inputs.

***Keywords*—**Railway suspension, test rig modeling, material selection, SolidWorks, simulation.

I. Introduction

THE main objective of railway vehicle suspension system is to provide effective isolation from track disturbance to the bogie as known vehicle handling and ensuring good vehicle support, stability and directional control during worse track conditions as known vehicle ride comfort [1]. But there is a conflict between vehicle ride comfort and vehicle handling: on the one hand, to maintain the ride comfort of the vehicle body, suspension system has to provide a soft isolation from the track disturbance to the bogie whereas on the other hand a stiff isolation is required from the track disturbance to the bogie to prevent the wheel from track disturbance to maintain the good vehicle handling purposes [2].

To design the suspension system, the designers always has to face difficulties to choose the suitable suspension stiffness and damping parameters because of this conflict [3]. To overcome this problem various researches has been done in railway vehicle sectors. An active control law has been introduced into passive suspension system by researcher to resolve this problem in the automotive sector. But in railway sector active suspension system has been introduced very lately in 1970’s because of its highly expenses and lack of technology advancement [4].

In railway suspension system is a mechanism that separates the bogie from the wheel and bogie to the vehicle body. Basically in railway there are two types of suspension system present: one is primary suspension which is placed between wheel to bogie and other is located between bogies to the vehicle body which is called secondary suspension system. As railway is a very high weight vehicle, so various types of performance characteristics needs to be considered in order to design a good suspension system. The primary suspension mainly consists of springs, shock absorbers and linkages that connect a vehicle to its wheels like normal car suspension. On the other hand secondary suspension system is consists of mainly air spring. The function of secondary suspension system is to reduce the vertical acceleration of the vehicle body so that it can increase the passenger comfort as well as ride quality during worse situations [5].

The main characteristics of suspension system are having the ability to store, dissipate and to introduce energy to the system. Depending on the operating conditions there are three types of suspension system mostly used in practical which are passive, semi-active and active suspension system. Passive suspension is the traditional one which is consists of spring and damper. The parameters of passive suspension system are fixed and it’s an open loop system. So the performance of passive suspension system is depends on the condition of road profile. On the other hand if the suspension system is controlled by the external force is known as semi-active or active suspension system. The semi-active suspension also same as passive system meanwhile the difference is it has adjustable damping parameter which can provide better performance than passive system at worse track conditions [6]. In active suspension system besides basic mechanical parts it has some additional components such as sensors, force actuators, and controllers. By adding force actuator to the system active suspension provides better performance than passive suspension system. The function of controller is mainly controls the actuator actions depending on what data is receiving from the sensors whereas sensor is the part who gives the information of track profile to the controller [7].

The primary objective of this paper is to study on the railway vehicle characteristics and develop a railway vehicle test rig to improve the indoor vehicle suspension simulation testing on a quarter-car railway vehicle. As passengers’ comfort is directly related to the disturbance of vehicle body, main focus is to design a secondary suspension mechanism in modeling the test rig. Considering all the factors a vertical quarter car test rig

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This paper was submitted on December 4, 2015; revised on December 20, 2015; and accepted on December 27, 2015.

is designed and developed for railway vehicle and performed its simulation. By using this test rig, vertical dynamics of vehicle body can be investigated such as vehicle body acceleration, velocity and displacement with respect to track input.

II. Organization of the Paper

Firstly, the paper presents components selection strategy where selection of materials, track input, mass and spring are introduced and discussed. Secondly, system architecture and design has been considered with appropriate quarter car model, block diagram of the system, Solidworks design of the test rig. Thirdly, simulation and result analysis has been presented with proper table and graphs. Finally, the paper draws concluding remarks.

III. Components Selection Strategy

A. *Selection of Materials*

In every mechatronics system to build up a rig structure, components selection is a very important part which needs mass amount of knowledge and study on controller, power source, actuator, structure materials and test rig design [8]. The choices of materials depend on the stability, affordability, reliability, robustness, expertise, applications, function and support. Table I represents the comparison of some materials depending on their qualities and characteristics.

Table I Comparison of Various Materials Based on Qualities and Other Characteristics

Materials	Characteristics of the Materials			
	Weight	***Strength***	***Flexibility***	***Heat Sensitivity***
Aluminum	Light	Strong	Very Flexible	Heat Resistance
Steel	Heavy	Strong	Very Flexible	Less Sensitivity (with compare to other steel)
Iron	Very heavy	Very Strong	Not Flexible	Heat Resistance
Wood	Light	Very Weak (easy to have a crack)	Flexible	Sensitive

As the frame is directly connected to the weight and component accommodation, aluminum was selected as the primary construction material. The reason behind choosing aluminum is low cost, high strength to weight ratio, availability, and versatility in joining. The shape and size of the frame was selected based on the internal components such as damper, motor etc. The stainless steels rod is selected to fit the aluminum plate which has the ability to corrosion resistance and staining, low maintenance, relatively low cost, and familiar luster make it an ideal material for this project.

B. *Mass and Spring Selection*

The most important thing of the suspension system design is that the system resonances should be occurred outside of the operating bandwidth. So the rig has been designed carefully to ensure the main resonance of the mass and spring occurs at the typical operating frequency. The resonant frequency has been chosen around 10Hz to ensure that the suspension deflection is sufficient for performance alterations and also can observe by naked eye. This chosen resonant frequency is also good for the operating bandwidth of the actuator to apply damping. As railway vehicle body is a very heavy weight vehicle, so in rig design the whole system has brought down into a small scale ratio. As a result the choice of values of mass and spring rate gets limited with respect to chosen resonant frequency. To select the motor with the desired torque, it is necessary to calculate the mass of both bogie and vehicle body. The general equation of calculating mass is given in (1) where, ρ is the density of selected material. Whereas l, w and d are indicating the length, width and depth of the selected material.

$$m = \rho \times (l \times w \times d) \quad (1)$$

Again by applying Hooke's law and the concept of simple harmonic motion, the angular frequency of mass on a spring or spring constant can be calculated. The equation 2 represents the relationship between both of them.

$$f = \frac{1}{2\pi}\sqrt{\frac{k}{m}} \quad (2)$$

$$k = 4\pi^2 f^2 m = 29600\ N/m \quad (3)$$

In the end the values of the mass is selected of 7.5kg and the total spring rate of 29600N/m which can provide a desired resonant frequency of 10Hz.

C. *Track Input*

To observe the suspension's performance it is important to introduce the disturbance input to the system. Driving the system through a frequency range of 0.1Hz to 10Hz is appropriate for the scale of the system. The suspension response in this range should be providing extensive performance with respect to the chosen design of test rig and material selection. There are three different categories of motors available which are known as stepper motor, DC motor and servomotor. Among of them DC motor is the most suitable one to produce disturbance into the suspension rig. The motor type is chosen by considering suitability, intended to usage, cost effective, availability and physical characteristics like weight to size ratio. It is very important part of the project because it can cause over budget, bring trouble and difficulty during experiment. Another important factor is the torque estimation which should satisfy the requirements to allow the desired movement of the rig. The solution developed was to use an electric DC motor which is mechanically coupled to a set of linear guides to convert the rotors rotational motion into linear motion. To calculate the torque of the DC motor can be given by in (4),

$$\tau = \mathrm{Fr}\sin\theta \text{ Or}, \tau = \mathrm{I}\alpha \quad (4)$$

Where, τ is the required torque, r is the displacement vector, F is the applied force, I indicates the moment of inertia and α is for angular acceleration.

Now the required torque is, $\tau = Fr\ sin\ \theta = \ 0.67N - m$, so the torque requirement to lift the mass is roughly need about 0.67N-m and the highest frequency (10Hz) only requires a drive frequency of 600rpm.

IV. System Architecture and Rig Design

Design of the test rig reflects the fundamental elements of a quarter car model as presented in **Figure 1**. According to **Figure 1**, m_v is indicating the sprung mass of vehicle body. On the other hand m_b denotes the unsprung mass of bogie and wheel assembly. A basic suspension system is placed in between m_v and m_b where k and c are representing spring and damper co-efficient respectively. Mass displacements of vehicle body and bogie are indicating by z_v and z_b. Track disturbance input is denoted by z_r which is generated by an electric motor placed in between m_b and ground.

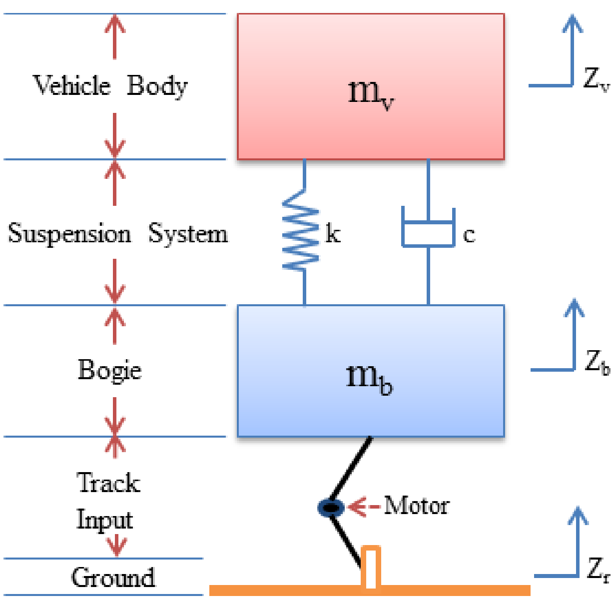

Figure 1 Quarter car model

The electric motor is able to produce oscillation up to 10Hz. The main function of the motor is to produce irregular track input to the system. As the track disturbance is generated, it will immediately transfer to the bogie, and then pass to the vehicle body through the suspension system. Because of the suspension system, the disturbance (oscillation) that induced on vehicle body will be reduced. **Figure 2** presents a block diagram that reflects the whole mechanism of the system.

For the system architecture it has been clarified that the suspension system will be movable close to at least 1Hz which can easily be observed by eye. The track input should create excitation between 0.1Hz to 10Hz based on the mechanical system design. The rig of the suspension system has designed concentrating on some important aspects such as:

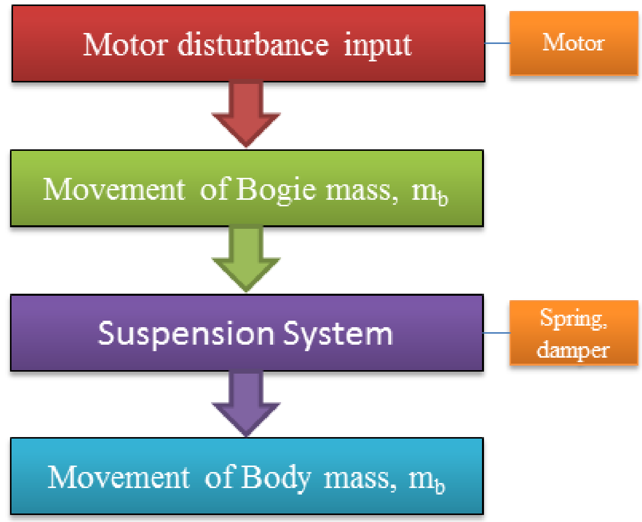

Figure 2 Block diagram of the whole system

- Disturbance input must provide in linear direction to the system.
- Rig has to support the mass, spring and constrain into linear direction while they are in moving position.
- Must be strong enough to hold the drive and mass movements within the target frequency range.
- Should produce similar dynamic actions under certain conditions such as nonlinearities, damping and resonance frequencies of chassis and wheel mass.
- The rig will provide ideally frictionless vertical guidance to the chassis mass.

After selecting the masses, behavior of the spring and the track input method the rig frame was designed. As the rig frame is the only part which will hold the whole system together such as the mass, springs, track input and other selected hardware, so this was an important stage of the project to design the frame very carefully. There is certain advantage having perfect rig frame for the system such as it will allow the suspension to work correctly, free from undesired vibrations and to be robust enough in active condition. Several designs have been drawn up concentrating on the component requirement. The selected design was chosen mainly due to its intuitive layout being very similar to a typical diagram of a suspension system.

Figure 3 represents the whole test rig design of the suspension system for railway. As it shows that the selected test rig consists of sprung mass as vehicle body, suspension elements, and unsprung mass as bogie, wheel, excitation plate, and linear sliding bearings. The sprung mass and unsprung masses are connected together by the suspension elements and all the moving parts are conducted through columns by linear sliding bearings.

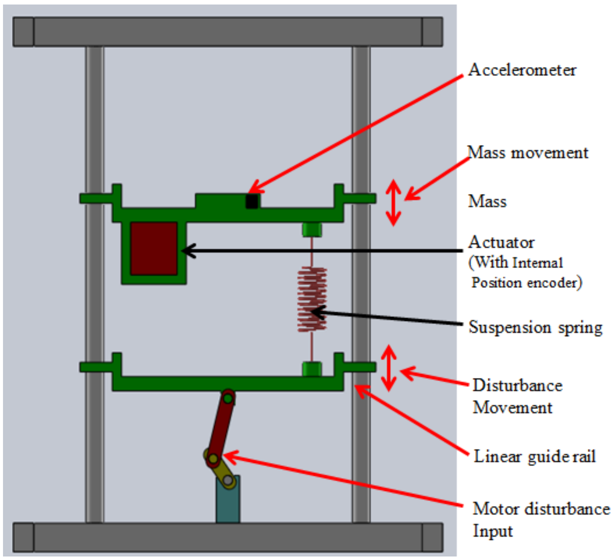

Figure 3 Suspension rig design for railway vehicle

V. Simulation and Analysis

The selected test rig was planned to be simulated analytically on SolidWorks software to take a reference readings which will use in the later part of the project. The main objective was to find out the required torque and power consumption needed for the system, vehicle body and bogie acceleration, vehicle body and bogie displacement based on the selected parameters and track input. The parameter used for this project is summarized in **Table II**.

Table II Parameter Used for the Simulation

Parameters	Symbols	Units	Values
Total mass	m	kg	7.5
Linear displacement of motor	r	mm	90
Motor constant speed/frequency	f	rpm	600
Spring constant	k	N/m	29600.00
Damping constant	c	N/(m/s)	660.00

Figure 4 shows the layout of the SolidWworks software, where the simulation has been done for this project. The value of the masses was selected of 7.5kg and the total spring rate was selected of 29600N/m which can provide a resonant frequency of 10 Hz.

For the track input an electric motor of constant 600 rpm is used which was equivalent to the 10 Hz. These plots represent the variations of body acceleration and suspension deflection significantly with respect to choosing parameters according to the vehicle speed. With the increasing of speed the vehicle body travel is fluctuating with higher amplitudes. Also the frequency of body acceleration is increasing significantly with increasing vehicle speed. The amplitude of suspension deflection also varying with respect to selected speed. The response of the suspension system based on the track input has been plotted such as vehicle body and bogie acceleration (m/s^2), vehicle body and bogie displacement (m), required torque (N-m) and power consumption (W) with respect to time (sec) which has been shown from **Figure 5** to **Figure 10**.

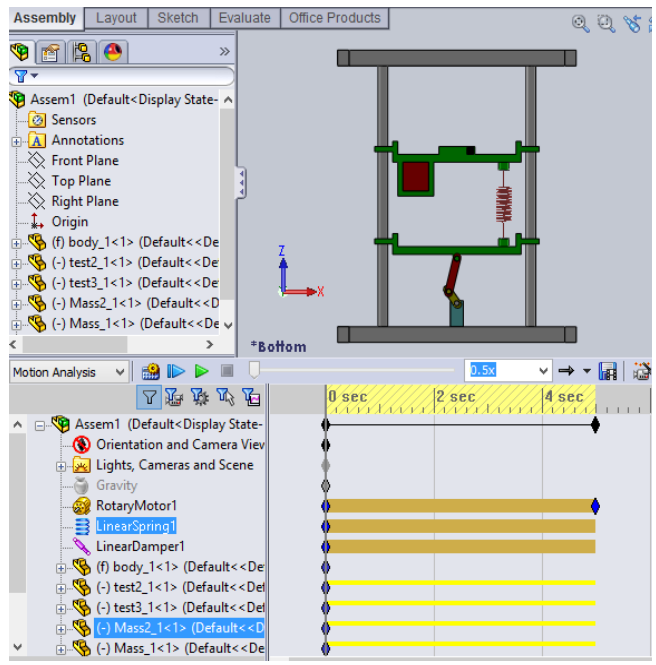

Figure 4 Layout of the SolidWorks software

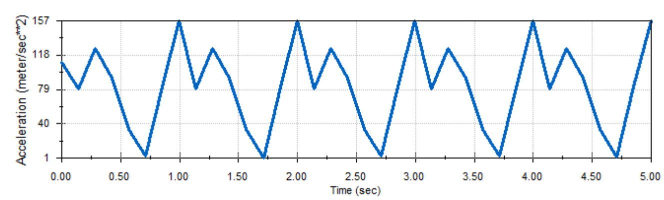

Figure 5 Vehicle body acceleration

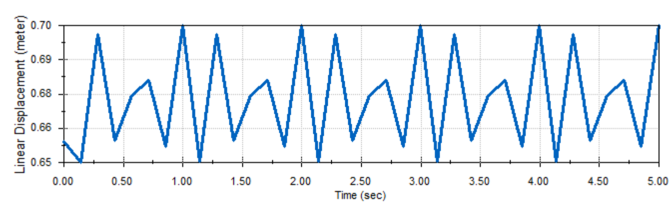

Figure 6 Vehicle body displacement

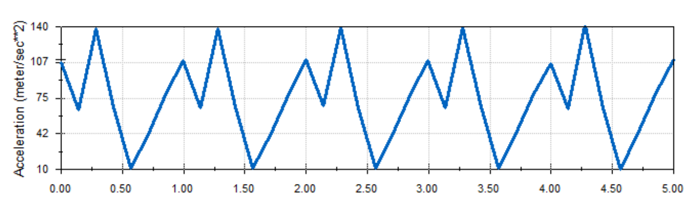

Figure 7 Bogie acceleration

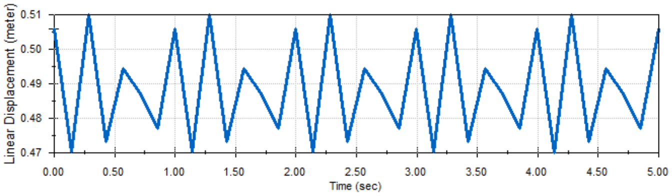

Figure 8 Bogie displacement

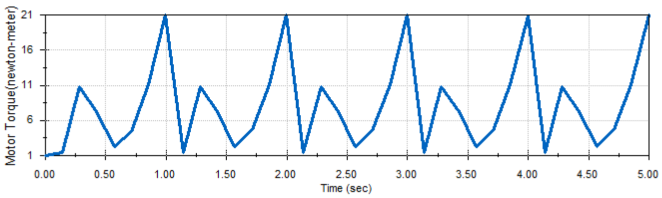

Figure 9 Total torque required for the system

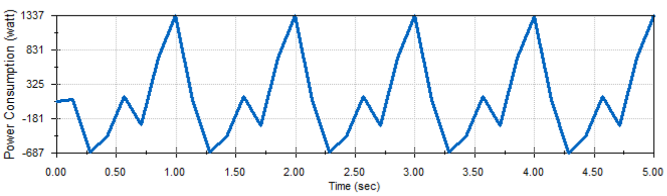

Figure 10 Power consumption of the system

VI. CONCLUSIONS

In the summary it can be concluded that the designed mechanical suspension rig meets the aim of the project of providing the ability to demonstrate vehicle body displacement for railway car from a disturbance input. The rig design and motion analysis has been done by using SolidWorks motion study which can provide various disturbance input under different conditions. Figure 2 shows the design layout of the suspension test rig. The main objective of this project was to find out the required torque and power consumption needed for the system, vehicle body and bogie acceleration, vehicle body and bogie displacement based on the selected parameters and track input.

For the future work, a physical suspension test rig will be developed based on the analysis has done in this project. This test rig will be used for reducing of vibration in active secondary suspension system of railway vehicle.

ACKNOWLEDGMENT

Authors would like to express their gratitude to the Ministry of Higher Education (MoHE), Malaysia to support the project through Research Acculturation Grant Scheme (RAGS).

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