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SEMI-ACTIVE TRAIN BOGIE SUSPENSION USING SKYHOOK DAMPERS

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Abstract

This research is conducted to demonstrate advantages of skyhook semi-active dampers in railway vehicle suspension system. Semi-active suspension consists of four actuators on each bogie that locate in the secondary suspension position instead of passive dampers. Employing equations of skyhook control policy, the semi-active damping force (actuator force) is determined using absolute velocity of car body instead of relative velocity. An integration of a control design software, i.e. MATLAB, together with a software for railway vehicle simulation, i.e. ADAMS/Rail is utilized for modelling and control analysis simultaneously. Analysis has been performed on a traditional bogie model with passive secondary suspension and on a new bogie model with active suspension. The effects of suspension system on displacement and acceleration in passenger seats have been investigated in various points of car body. Results demonstrate that semi-active suspension improves the ride comfort by reducing accelerations, in comparison with passive model. Skyhook dampers can improve the dynamic behaviour of a railway vehicle. The simplicity of skyhook damper implementations makes it suitable for the performance improvement of passive systems.

INTRODUCTION

Semi-active dampers have been used for more than two decades. Introduced by Karnopp and Crosby [1] in the early 1970's, semi-active dampers have most often been studied and used for vehicle primary suspension systems. The virtues of active and semi-active dampers versus traditional, passive dampers have been addressed in many studies [2-5].

As technology advances, semi-active suspensions continue to gain considerable attention. Semi-active suspensions consist of a spring element and a damper which offers variable damping. Whether through mechanical changing orifices or fluid with adjustable viscosity, a semi-active damper has the ability to adjust the damping level.

There is also stochastic excitation caused by wheel and rail roughness that mainly dominates the mid- and high-frequency regimes. In the lower-frequency domain the tonal components are relevant. Due to this tonal nature of excitation an active vibration control solution is appropriate [6].

The core of this work is to evaluate the benefits of skyhook control policy under steady-state sinusoidal inputs for a railway vehicle. A simple suspension model that can be used for skyhook damper is shown in Fig.1. Since the model represents a single suspension from one of the four corners of a vehicle, this 2-degree of freedom (2DOF) system is often referred to as the "quarter-car" model that was used in previous studies [7]. The mass of the car body, the bogie frame and the wheelset assembly (unsprung mass) are defined respectively by M_1, M_2 and M_3, with their corresponding displacements defined by X_1, X_2 and X_{in} , and car body and bogie frame velocities V_1, V_2, respectively. The relative velocity, V_{12}, is defined as the velocity of the car body mass (M_1) relative to the bogie frame mass (M_2). The primary suspension is made of a spring element, K_P, and a damper, C_P. The secondary suspension stiffness and damping coefficient are represented by K_S and C_S respectively. In order to implement the semi-active control, a skyhook damper will be used in place of a passive damper. Figure1 parameters are introduced below.

M_1 car body mass
M_2 bogie frame mass
M_3 wheelset mass
K_P primary suspension stiffness
K_S secondary suspension stiffness
C_P primary damping coefficient
C_S secondary damping coefficient
X_1 car body displacement
X_2 bogie frame displacement
X_{in} input displacement
V_1 car body velocity
V_2 bogie frame velocity

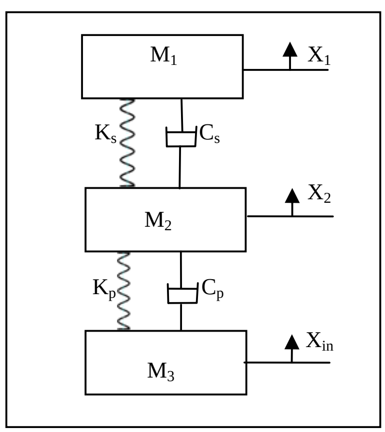

Figure 1 – 2DOF quarter vehicle model

SEMI-ACTIVE CONTROL METHODS

In semi-active suspensions, the damping force is adjusted by a controller that may be programmed with any number of control schemes. The control schemes that are commonly used for vehicle suspensions include:

- On-off Skyhook
- Continuous Skyhook
- On-off Groundhook
- Continuous Groundhook
- Hybrid Control
- Fuzzy Logic Damping Control
- Sliding Mode Controller

A detail description of the above control methods can be found in many past studies, including [8–11]. Among these methods, continuous skyhook control was selected for our simulation study, due to its effectiveness in controlling body dynamics.
The equations governing skyhook control can be described by:

$$\begin{array}{ll} V_1 V_{12} > 0 & F_{sa} = G_s V_1 \\ V_1 V_{12} < 0 & F_{sa} = 0 \end{array} \tag{1}$$

where

V_1 = absolute velocity of the car body mass with respect to the ground,

V_{12} = relative velocity between the car body and bogie frame masses,

F_{sa} = semi-active damping force, and

G_s = is a gain factor such that the full damping range of the controllable damper can be used.

VEHICLE MODEL

The vehicle model consists of a rigid car body, suspended on two bogies. ADAMS software has been utilized for building the model. Each bogie has primary and secondary suspension system. Primary suspension contains four vertical passive dampers and eight springs, linked the bogie frame to wheelsets. Secondary suspension contains four vertical spring and two diagonal passive dampers that connected the bogie frame to bolster. In semi-active suspended model, four actuators exist as secondary suspension in place of secondary passive dampers. Bumpstops with non-linear characteristic located on bolster. The complete models of the bogie and car body, built in ADAMS software environment, are shown in Figure 2 and figure 3 respectively.

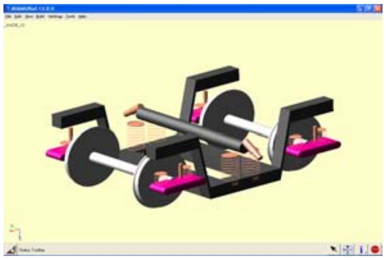

Figure 2 - ADAMS model of the bogie

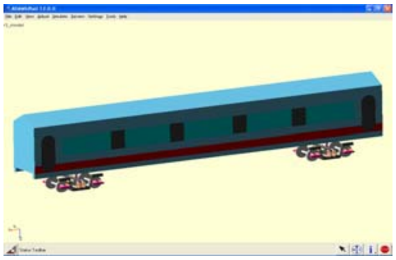

Figure 3 - ADAMS model of the coach

Track model consists of a straight track with vertical irregularities on rail surface. These irregularities were modelled by sinusoidal displacements imposed under wheels at contact point. Since the irregularities have random shape, they can induce every frequency to the model in real condition. Regarding this fact the dynamic response of vehicle model should be analyzed in all frequencies. The chirp signal was used in our study to cover all frequencies. The plots are presented here relate to 0 HZ to 50 HZ frequency range that contains almost all frequencies of our vehicle model.

CONTROL STRATEGY

ADAMS/Control and MATLAB have been used for control system modelling and design in this work. The active actuators were modelled in ADAMS environment. ADAMS plant was exported to MATLAB and the control loop was built with MATLAB. The closed loop analyses were performed with MATLAB 6 and ADAMS 12 . All of the co-simulations have been done interactively in discrete mode.

The outputs of the ADAMS plant are absolute velocity of the car body mass with respect to the ground (V_1) and relative velocity between the car body and bogie frame masses (V_{12}). With these two signals and regard to the equations governing skyhook control policy, the semi-active damping force (actuator force) is determined in MATLAB/SIMULINK environment. This force is the ADAMS plant input. The actuators are located in secondary damper positions and act as an active secondary suspension. Each bogie has two actuators that control the bolster motion. A sample of MATLAB/ADAMS co-simulation is illustrated in Figure 4. There are two outputs from ADAMS Plant (absolute velocity of the car body and relative velocity between the car body and bogie frame) that enter to MATLAB control block and the output of control system block (actuator force) is the ADAMS plant input.

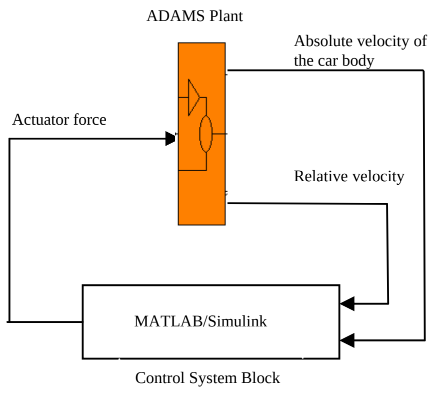

Figure 4 - ADAMS and MATLAB combined simulation

SIMULATION CONDITIONS

Two models have been used in our simulations. First model is the original model that has passive dampers as secondary suspension and the other model contains semi-active secondary suspension that consists of four actuators placed in passive damper's position. Here the vehicle models were subjected to a sinusoidal input motion that imposed under two left wheels of rear bogie. The comparative output is acceleration in passenger seats above rear bogie. Indeed the vertical irregularities on rail surface were modelled by these vertical motions. The frequency of input depends on many factors like vehicle's speed. Here the simulations have been performed in various frequencies of input wave motions. The frequency range contains 0 to 50 HZ that swaps most of the natural frequencies of vehicle. The variable frequency is a linear function of time with a slop that equals to 5 (f = 5t). At the beginning the frequency is 0 HZ and by time passage it increases step by step, for example after 5 seconds the input frequency arrives to 25 HZ. Figure 5 shows vertical input displacement with variable frequency vs. time for 5 seconds. The magnitude of sinusoidal irregularities has a constant value that equals to 1mm.

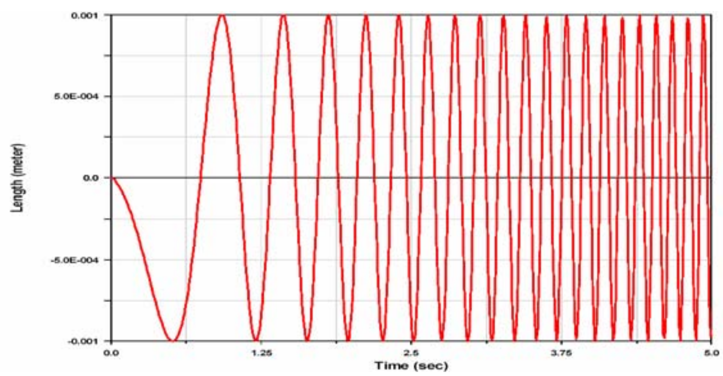

Figure 5 - Variations of vertical input displacement vs. time under wheels

In the closed control loop, embedded sensors measure the absolute velocity in upper point of actuator connected to the bolster and feedback them into a central PC to determine the actuator forces. This is the main difference between active skyhook dampers and passive dampers that in active systems absolute velocity is used instead of relative velocity. In various points of the car body, acceleration, velocity and displacement were measured in passenger seat positions that have been used for analysis and comparison of models.

SIMULATION RESULTS

As demonstrated in figure 6 and Figure 7 the magnitude of acceleration measured in passenger seat above rear bogie due to vertical wheel excitations, has decreased using semi-active skyhook secondary suspension. The magnitude of acceleration reaches to 10 m/s^2 after 10 seconds in passive model while it can be reduced to 5 m/s^2 by semi-active dampers. It means that we can nearly double the ride quality by a simple semi-active suspension system like skyhook dampers. The solid curves are related to original model with passive secondary dampers and the dashed curves represent semi-active suspension. Figure 8 shows force magnitude of one actuator in the new model of bogie with semi-active suspension during 10 seconds of analysis.

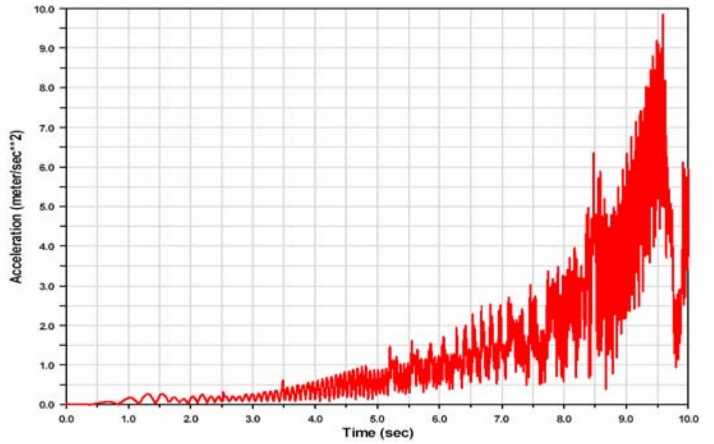

Figure 6 - Variations of acceleration magnitude in passenger seat vs. time (Passive suspension)

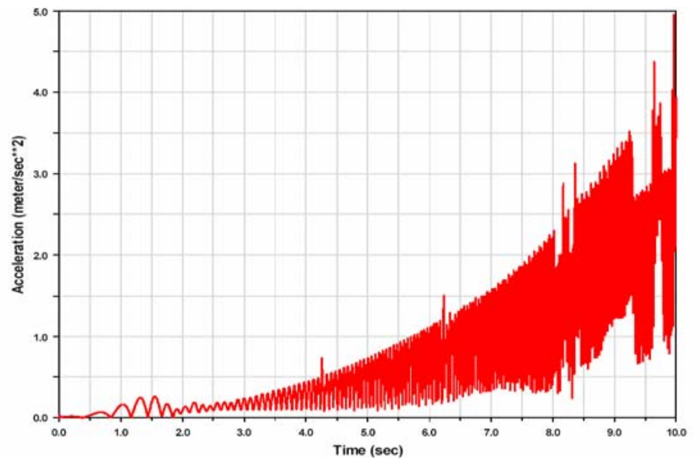

Figure 7 - Variations of acceleration magnitude in passenger seat vs. time (Semi-active suspension)

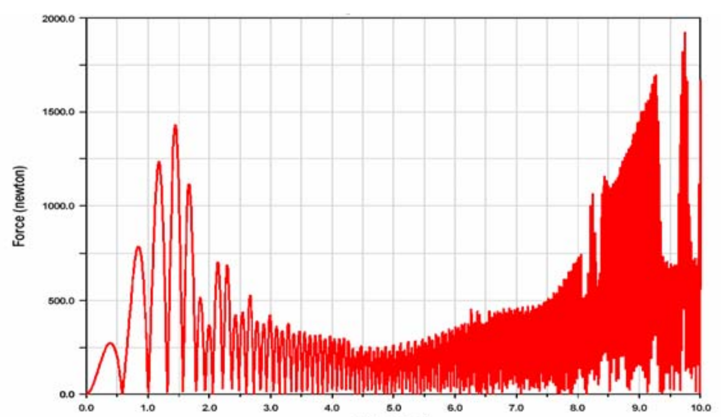

Figure 8 - Variations of actuator force magnitude vs. time

The vertical displacement and acceleration measured in passenger seat above rear bogie are displayed in figure 9 and figure 10. Similar results are obtained in both plots and confirm that semi-active skyhook damper decreases displacement and acceleration. It is more obvious in Figure 11 that particularly in reign between 9th and 10th second with maximum response amplitude, the semi-active suspension act perfectly.

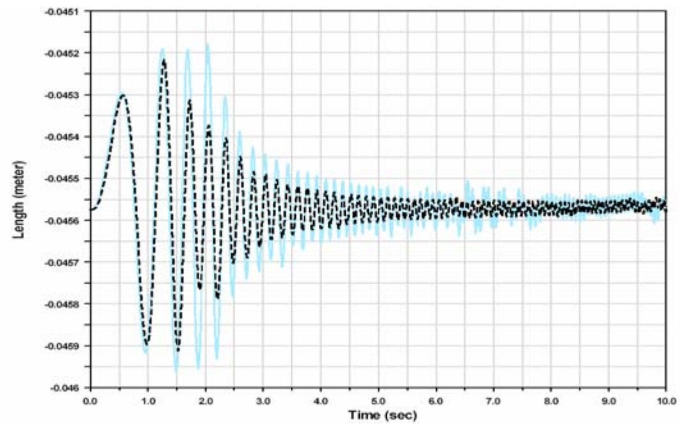

Figure 9 - Variations of vertical displacement in passenger seat vs. time, Solid curve is related to passive and dash one to semi-active suspension

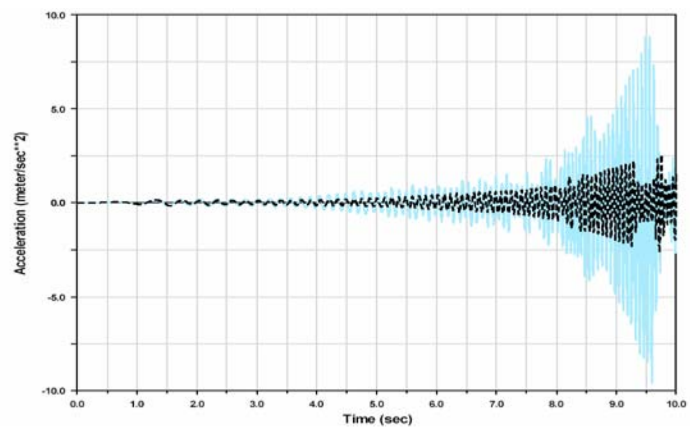

Figure 10 - Variations of vertical acceleration in passenger seat vs. time, Solid curve is related to passive and dash one to semi-active suspension

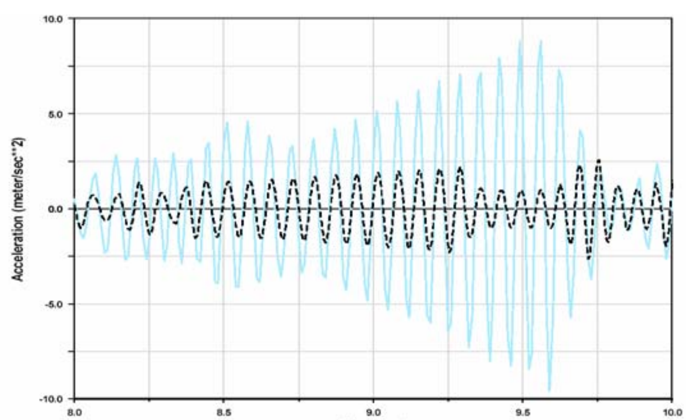

Figure 11 - Variations of vertical acceleration in passenger seat vs. time (zoomed in 8th to 10th second), Solid curve is related to passive and dash one to semi-active suspension

CONCLUSIONS

Replacing the traditional passive secondary dampers of a railway vehicle by simple semi-active skyhook dampers, can reduce the displacement and acceleration magnitude. As illustrated in Figure10 using semi-active damper has decreased the acceleration to half of magnitude. This reduction in the acceleration magnitude culminates in ride comfort improvement in passenger seats. Skyhook dampers can improve the dynamic behaviour of a railway vehicle by increasing stability. The simplicity of skyhook damper implementations makes it suitable for the performance improvement of passive systems. Particularly, in high speed trains, passive dampers can not meet the ride requirements, thus active or semi-active suspension systems seem necessary.

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