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STABILITY ENHANCEMENT OF RAILWAY VEHICLE DYNAMICS PERFORMANCE IN LATERAL DIRECTION USING FUZZY BOGIE-BASED SKYHOOK CONTROL

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ABSTRACT

Increasing requirement in railway vehicle technologies regarding on riding comfort, running safety and speed of railway vehicles are in the increasing trend of studies today. These requirements are opposed by the fact that the condition of the tracks is getting worse and maintenance cost is becoming expensive. In view of this conflict, conventional suspension concepts are not able to overcome all these problems. This paper investigates the performance of semi-active control of lateral suspension system namely fuzzy body-based skyhook and fuzzy bogie-based skyhook for the purpose of attenuating the effects of track irregularities to the body lateral displacement, body roll angle and unwanted yaw responses of railway vehicle. The controller is optimized on 17 degrees of freedom railway vehicle dynamics model and showing better dynamics performance than its counterparts.

Keywords: magnetorheological damper, carbody, bogie, wheel sets.

INTRODUCTION

With increased railway vehicle speeds, the vehicle's dynamic performance is negatively affected. The suspension of the vehicle has to be modified in order to compensate for the deteriorated dynamic behavior. However, improvement possibilities by means of passive suspension technology will eventually reach a limit. Therefore, active suspension technology in railway vehicles is considered as an alternative solution for this issue, since it offers better possibilities of improving the vehicle's dynamic performance compared to the conventional passive solution.

Active technology in rail vehicles can be divided into two general categories: the first is for improving running stability and wheelset guidance through the use of controllable primary suspension and the second is for improving passenger ride comfort through various modifications of secondary suspension [1]. This research concentrates on the secondary suspension concept, concerning ride comfort improvements by means of electronically controlled lateral suspension system.

An electronically controlled suspension system consists of actuators, sensors and a specific control law, which generates the force demand for the actuator. The actuator should be able to generate the demanded control force in attenuating unwanted vehicle body motions. How well this is done depends on the characteristics of the actuator. There are various types of actuators that can be applied in railway vehicles, such as electro-mechanical, electro-magnetic, hydraulic, servo-pneumatic and rheological (electrical or magnetic) systems. Together with the actuator an appropriate control strategy has to be chosen. One of the most implemented and analyzed suspension control strategy during the years is skyhook.

In automotive systems, the skyhook principle for the suspension control has been widely investigated [2, 3, 4, 5]. The principle consists in applying a force through the actuators installed between the car body and the wheel. This force corresponds to the force of a damper for the car body and wheel acting against the inertial frame [6]. Like most other methods of comfort improvement, the skyhook principle in railway vehicle sets its focus on the reduction of the effects of external disturbance due to track irregularities.

Fuzzy and skyhook control are investigated in this study namely fuzzy bogie-based skyhook and fuzzy body-based skyhook. Fuzzy bogie-based skyhook is a virtual damper attached between bogie and the sky to damp out unwanted vibratory motion of the bogie and to prevent the motion to be transmitted to the body. Likewise for fuzzy body-based skyhook, the virtual damper is attached between the body and the sky. This paper is organized as follows: the first section presents introduction and review of some related works, followed by mathematical derivations of 17-DoF railway vehicle model in the second section. The third section introduces the proposed control structure for the active lateral suspension system. The improvements on railway vehicle dynamics performance in terms of reducing body roll angle, unwanted yaw and unwanted lateral displacement responses using the proposed control strategy are presented in the fourth section. Finally, the last section presents some conclusions.

METHODOLOGY

Railway vehicle model considered in this study consists of a carbody connected to four wheel sets via two bogie masses and is represented as a 17-DoF railway vehicle model system. The 17-DoF of railway vehicle model system consists of carbody dynamics with 3-DoF: lateral displacement, yaw motion, roll motion; Bogies dynamics with 6-DoF: lateral displacement bogie 1, lateral displacement bogie 2, yaw motion bogie 1, yaw motion bogie 2, roll motion bogie 1, roll motion bogie 2; Wheel sets dynamics with 8-DoF: lateral displacement wheel set 1, lateral displacement wheel set 2, lateral displacement wheel set 3, lateral displacement wheel set 4, yaw motion wheel set 1, yaw motion wheel set 2, yaw motion wheel set 3 and yaw motion wheel set 4.

The carbody and bogie masses are allowed to roll and yaw as well as to displace in lateral direction. Each wheel set is allowed to yaw and displace in lateral direction. Figure-1 shows the plain view and front view of 17-DoF railway vehicle model with lateral suspension system. The equations of motion for the 17-DoF was derived based on the Newton's law and based on the similar model in Ma and Yang (2008). For detailed observation the effect of the lateral displacement, yaw angle response and roll angle response, the 1:10 scale railway vehicle test rig has been developed in Autotronic Lab, Universiti Teknikal Malaysia Melaka. The railway vehicle test rig as shown in Figure 2 was developed based on 17-DOF full railway vehicle model have been developed using Matlab Simulink software.

Figure-1 shows the plain view of 17 DoF railway vehicle model with lateral suspension system. The equations of motion for the 17 DoF was derived based on the Newton laws and the similar model was used by [7].

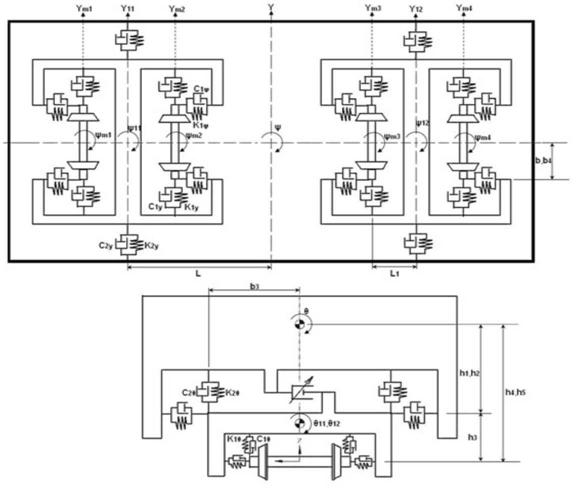


Figure-1. 17-DoF railway vehicle model.

Spencers *et al.* [8] proposed the so called Bouc-Wen model in order to characterise the behaviour of a magnetorheological damper. This concept is based on an approach of Wen [9]. Mechanical analogue of the Bouc-Wen model is indicated in Figure-2. The force generated by the device is given by

$$F = c_0\dot{x} + k_0(x - x_0) + \alpha z \tag{1}$$

where the hysteretic component z satisfies the following
equation.

$$\dot{z} = -\gamma|\dot{x}|z|z|^{n-1} - \beta\dot{x}|z|^{n} + \delta\dot{x} \tag{2}$$

By adjusting the parameter values of a, b, g, d and *n*, it is possible to control the shape of the force-velocity characteristic.

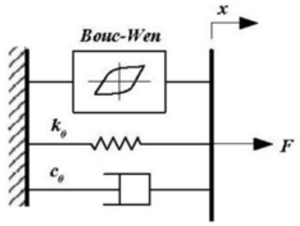


Figure-2. Mechanical analogue of the Bouc-Wen model.

The controller structure implemented in this study is depicted in Figure-3 which consists of two loops namely outer and inner loops. The outer loop is used for disturbance rejection control to reduce the unwanted vehicle's motions. The inputs of the outer loop controller are vehicle's states namely body velocity and wheel velocity. Whereas, the output of the outer loop controller is the target force that must be tracked by the MR damper. On the other hand, the inner loop controller is used for force tracking control of the MR damper in such a way that the force produced by the MR damper is as close as possible with the target force produced by the disturbance rejection control.

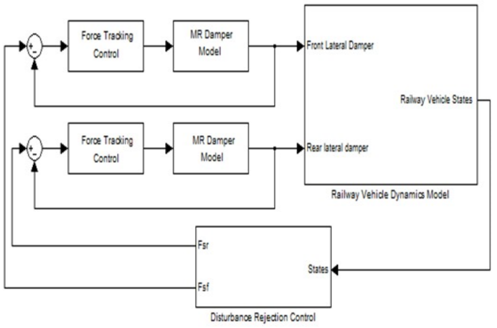


Figure-3. The controller structure of semi active suspension system.

Skyhook control strategy was introduced by Karnopp [6], in which a fictitious damper is inserted between the sprung mass and the stationary sky as a way of suppressing the vibratory motion of the sprung mass and as a tool to compute the desired damping force. In this study two types of skyhook control was implemented namely body-based and bogie-based skyhook as illustrated in Figure-4. The equation governing body-based skyhook controls for front and rear lateral dampers are expressed as:

$$F_{sf,bod} = C_{body}(\dot{Y} + L\dot{\psi}) \tag{3}$$

$$F_{sr,bod} = C_{body}(\dot{Y} - L\dot{\psi}) \tag{4}$$

Whereas, the equation governing body-based skyhook controls for front and rear lateral dampers are expressed as:

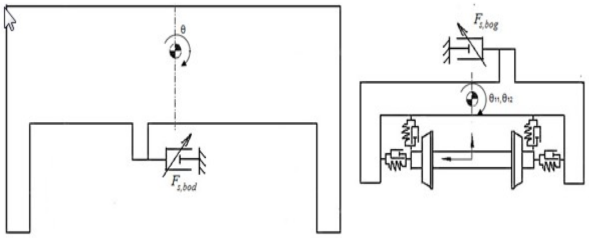
$$F_{sf,bog} = C_{bogie}\dot{Y}_{11} \tag{5}$$

$$F_{sr,bog} = C_{bogie}\dot{Y}_{12} \tag{6}$$

where $F_{sf,bod}, F_{sr,bod}, F_{sf,bog}$ and $F_{sr,bog}$ are front and rear body-based and bogie-based skyhook damping forces, respectively. The damping constants for body-based and bogie-based skyhook namely C_{body} and C_{bogie} are determined with the following rule:

$$C_{body} = \begin{cases} C_{body,\max} & \text{if} \quad V_{body} x V_{rel} \geq 0 \\ C_{body,\min} & \text{if} \quad V_{body} x V_{rel} < 0 \end{cases}$$

$$C_{bogie} = \begin{cases} C_{bogie,\max} & \text{if} \quad V_{bogie} x V_{rel} \geq 0 \\ C_{bogie,\min} & \text{if} \quad V_{bogie} x V_{rel} < 0 \end{cases}$$



(a)Body-based Skyhook (b) Bogie-based Skyhook

Figure-4. Body Skyhook and Bogie Skyhook.

However, it should be noted that the conventional skyhook algorithm treats all conditions without considering the moving direction between railway vehicle carbody and bogies. To overcome this problem, fuzzy logic control approach is adapted in these body-based skyhook and bogie-based skyhook control. Fuzzy logic is good to handle such a need because the desired damping constant can be determined by considering the moving direction between railway vehicle carbody and bogies. The output of the controller as determined by the fuzzy logic may exist between the high and low states damping. In fuzzy logic development, it is important to define certain parameters and conventions that will be used throughout the controller development. Referring to the Figure-2 and Figure-3, for all sign assignment, the movement of railway vehicle carbody and bogies are positive in clockwise direction.

Fuzzy logic control consists of the fuzzification of the controller inputs, the execution of the rules of the controller and the defuzzification of the output to a value to be implemented by the controller. The first step of a fuzzy logic controller is the fuzzification of the controller inputs which is accomplished through the structure of a membership function for each of the input. In the railway vehicle system, the fuzzy logic is designed with two inputs including the carbody lateral velocity *Vbody*and the relative velocity of the carbody and bogies *Vrel*. The possible shapes of these membership functions are infinite, though the shape that most widely used are the triangular-type, trapezoidal-type, Gaussian-type and singleton membership functions. In this study, a Gaussian-type is used for each input. Each membership function is defined by three linguistic variables, Negative (N), Zero (Z) and Positive (P) and is symmetric about zero. Figure-4 and Figure-5 define each input and their membership functions,

The second step is the execution of the rule of the controller where the generic form of the fuzzy rule is as follows:

$$\{\text{If } V_{body} \text{ is (A) and } V_{rel} \text{ is (B) then } C_d \text{ is (C)} \tag{7}$$

where A, B and C represent the linguistic values for the absolute carbody velocity, the relative velocity of the carbody and bogies and the desired damping coefficient. In this study, fuzzy type used is Sugeno type and therefore the prescribed output values are constant. The prescribed output values of the fuzzy systems are listed in Table-1 where the values are determined by choosing several damping constant values between the high and low states damping. The seven linguistic variables are as follows,

$$L = (C_{d1}, C_{d2}, C_{d3}, C_{d4}, C_{d5}, C_{d6}) \tag{8}$$

The rules of the system can now be developed. The fuzzy logic controller rule-base for the railway vehicle model is detailed in Table-2.

Table-1. Output values of fuzzy system.

L	**Value (**Newton**)**
Cd1	1985
Cd2	2353
Cd3	2732
Cd4	3158
Cd5	3588
Cd6	3831

Table-2. Fuzzy logic rule.

	Vrel		
Vbody	**N**	**Z**	**P**
N	Cd6	Cd2	Cd1
Z	Cd5	Cd3	Cd4
P	Cd1	Cd4	Cd6

The fuzzy logic of rule shown in Table-2 may be referred by skyhook based fuzzy logic control. By examining the rule table, it can be seen that the rule is in agreement with the skyhook policy since both the absolute carbody velocity and relative velocity of the carbody and bogies are fully negative or fully positive. The Cd6 is defined as the maximum damping coefficient and will be employed since two input variables have the positive or negative sign which is known to be fully positive. Where the product between each input variables has a negative sign, it can be called as fully negative in which the Cd1 is employed. However, when each input is not fully positive or fully negative, the fuzzy skyhook is used according to the membership function.

The last step is defuzzification which converts the fuzzy values obtained from execution of the rule tables into a single value. The output of the outer-loop controller is the desired damping coefficient Cd. However, the inner loop controller needs desired damping force Fd as the controller input. The desired damping force can be obtained by multiplying the desired damping coefficient with the damper velocity as follows,

$$F_d = C_d \times V_{rel} \qquad (9)$$

RESULTS AND DISCUSSIONS

Simulation works were performed in the Matlab-Simulink environment to investigate the performance of body-based skyhook and bogie-based skyhook. Track irregularities were modelled as a sine wave with the magnitude of 0.07 m and the frequencies of excitation of 1rad/sec, 3 rad/sec and 5 rad/sec. Three performance criteria are considered in this study, they are: body lateral displacement, unwanted body roll response and unwanted body yaw response at the body center of gravity.

The response of railway vehicle model for a sinusoidal track irregularity with the amplitude of 7 cm and 1 rad/sec excitation frequency are presented in Figures 5, 6 and 7 in which the solid line indicate the response of bogie-based skyhook, the dashed line indicate the response of body-based skyhook and the dotted line is the response of the passive system. Figure-5 shows that the body-based skyhook has significantly better performance in reducing lateral displacement response compared to passive and also shows slight improvement as compared to the fuzzy bogie-based skyhook.

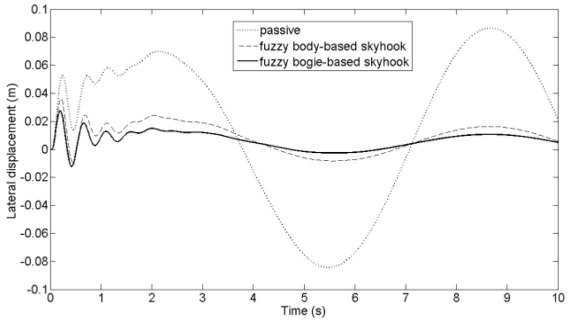


Figure-5. Lateral displacement response for 1 rad/sec excitation frequency.

In terms of roll angle and yaw angle responses, the fuzzy bogie-based skyhook is slightly better than the body-based skyhook and is significantly better than the passive system as shown in Figures 6 and 7. In can be said that the semi-active lateral suspension system with fuzzy bogie-based skyhook is able to minimize unwanted body roll and body yaw angle due to the track irregularity.

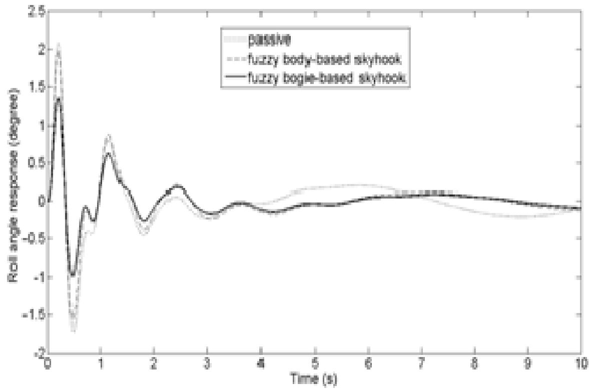


Figure-6. Roll angle response for 1 rad/sec excitation frequency.

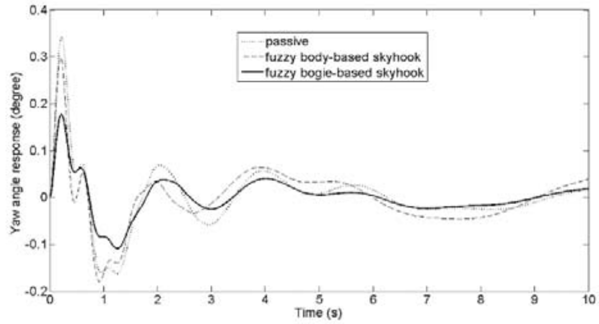


Figure-7. Yaw angle response for 1 rad/sec excitation frequency.

The response of railway vehicle model for a sinusoidal track irregularity with the amplitude of 7 cm and 3 rad/sec excitation frequency are presented in Figures 8, 9 and 10. From the Figures, it can be seen that bogie-based skyhook is able to damp out unwanted vehicle motion effectively and shows better performance in all three performance criteria compared to body-based skyhook and the passive system. This is due to the fact that bogie-based skyhook is able to cancel out the effect of track irregularity before being transmitted to the vehicle body.

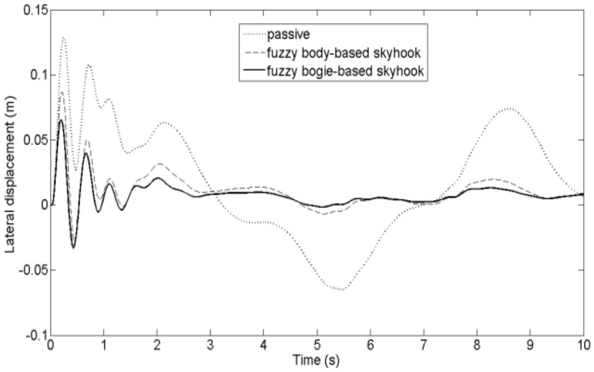


Figure-8. Lateral displacement response for 3 rad/s excitation frequency.

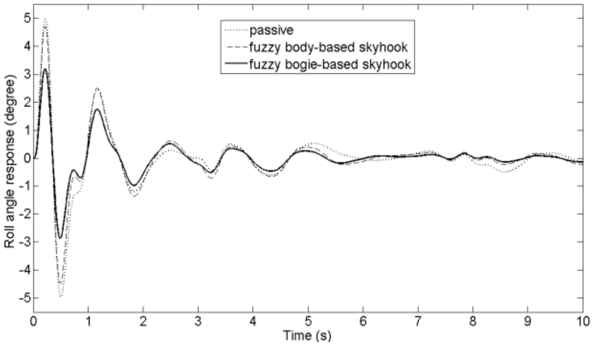


Figure-9. Roll angle response for 3 rad/s excitation frequency.

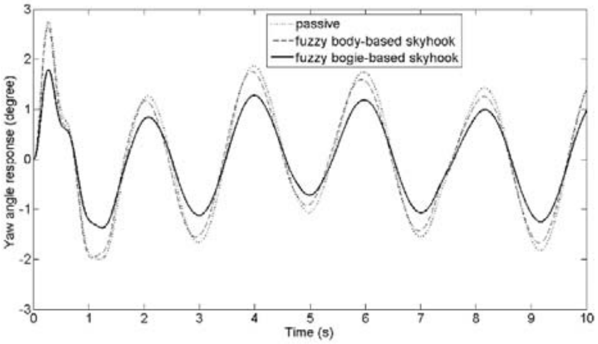


Figure-10. Yaw angle response for 3 rad/s excitation frequency.

The response of railway vehicle model for a sinusoidal track irregularity with the amplitude of 7 cm and 5 rad/sec excitation frequency are presented in Figures 11, 12 and 13. Similar trend with the response of 3 rad/sec excitation frequency are found from the figures where the bogie-based skyhook is able to eliminate unwanted vehicle motion effectively and shows better performance in all three performance criteria compared to body-based skyhook and the passive system. Again, this is due to the cancellation out effect of track irregularities of the bogie-based skyhook before being transmitted to the vehicle body.

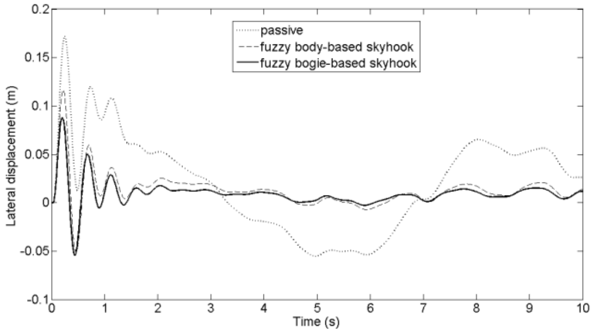


Figure-11. Lateral displacement response for 5 rad/s excitation frequency.

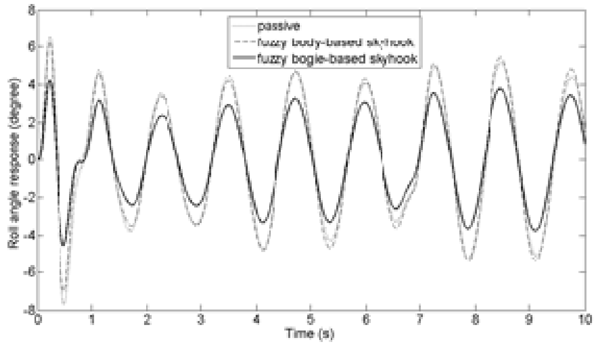


Figure-12. Roll angle response for 5 rad/s excitation frequency.

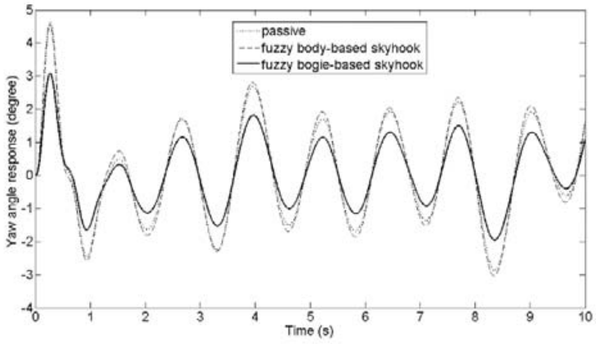


Figure-13. Yaw angle response for 5 rad/s excitation frequency.

CONCLUSIONS

17 DoF railway vehicle model, MR damper model along with fuzzy bogie-based skyhook and fuzzy

body-based skyhook have been developed and simulated. Sine wave track irregularity with the excitation frequencies of 1, 3 and 5 rad/sec was considered in this study. Performances of the two semi-active controllers were compared with passive system in terms of the body lateral displacement, body roll angle and body yaw angle. From the simulation results, fuzzy bogie-based skyhook can outperform the passive system as well as the fuzzy body-based skyhook and is able to improve all three performance criteria's.

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