A Study on Ride Improvement of a High Speed Train using Skyhook Control

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Abstract—This paper presents a semi-active suspension control system of a high speed railway vehicle with an observer-based skyhook control for ride comfort improvement. A semi-active suspension model can be represented as a quarter-car for observer design. An observer is formulated in order to provide the estimated state that contains the lateral velocities of a car body and a bogie which are calculated using some measured accelerations. The estimated states are used to compute the gains in skyhook control. A full scale railway vehicle is developed by an MBS (Multi-body system) tool. Also, to verify the developed model before running the simulation, lateral accelerations of a car body and a bogie are compared with results from an experimental roller rig test. In the dynamic analysis, the lateral behavior of a railway vehicle using skyhook control shows more stability than when using a passive system on the irregular track.

Keywords—High speed train, Multi-body dynamics, Ride comfort, Skyhook control

I. INTRODUCTION

Speed and transport capacity of railway vehicles keep increasing. Passengers require more comfortable and stable railway vehicles, but faster speeds of a railway vehicle on irregular track cause larger yaw and lateral motion of the train, and such motions of the train may make an uncomfortable ride. Thus, the role of a suspension system is important, because a suspension system improves ride comfort and reduces vibration of a railway vehicle on irregular track. However, most conventional suspension systems applied to present trains have limitations in improving ride comfort, so active and semi-active suspension systems are introduced. The performance of a semi-active suspension system is known to improve ride quality better than a passive suspension system, and its performance can approach the performance of an active suspension system with proper design. And the cost (energy consumption and actuators/sensors hardware) of a semi-active suspension system is lower than an active suspension system.

Semi-active suspensions of railway vehicles have been studied for several decades [1]–[3]. The control strategies of a semi-active suspension have also been studied for several decades, and such suspension systems have recently been commercialized in railway vehicles [4], [5]. The skyhook control strategy, among some of the controllers for semi-active system operation, has been presented by many authors.

The skyhook control system was proposed by Karnopp [6] in 1974 and its theory has been applied to several industries such as automotive, train systems and the landing gear of an airplane [7]. In this paper, the system is applied to a high speed railway vehicle. It can be controlled by the relationship between the velocities of two masses, an upper and a lower object. The velocities can be obtained by several methods involving the integration of accelerations from accelerometer signals and using hybrid analog/digital filters, as velocity is difficult to measure in practice [8]. For this reason, an observer design was proposed to predict velocities from accelerations or relative displacements of real systems. Many authors have proposed observer designs based on desired error dynamics, and various methods have been presented to estimate state of vertical behavior of an automobile [9]–[11]. However, the lateral behavior of a railway vehicle is an important design point of skyhook control for ride comfort, and there are very few papers on lateral state estimation. Also, many authors have worked on observers without external unknown disturbances such as road and track disturbance [8].

In this paper, a quarter-car model is developed for observer design and a full scale model of a railway vehicle is modeled using the MBS tool ADAMS/Rail. This paper investigates the performance of skyhook control to minimize lateral behavior, and its performance is compared with a passive system. The lateral velocities of a railway vehicle were estimated in unknown disturbance (track irregularities) using a state observer system, and velocity information are used to compute control gain. The proposed control strategy is convenient to use for semi-active suspensions and can easily measure the lateral state which can be applied to a railway vehicle suspension.

II. CONTROL STRATEGY

A. Skyhook control

The damper of a semi-active suspension has variable damping coefficients. These damping coefficients are modulated in the following admissible space:
\[ C_{\text{min}} \leq C_{\text{desired}} \leq C_{\text{max}} \] (1)

In this study, a control strategy of a semi-active suspension was applied to the skyhook control algorithm which is a concept developed in Karnopp’s work. A skyhook damper is a fictitious damper between a sprung mass and the inertial frame as described in Fig. 1.

Control systems for semi-active suspension dampers have been developed for a long time. Skyhook-controlled suspension is well known for its good performance for vibration reduction in some of the control systems. In this paper, this system was adopted to reduce the car body lateral behavior. The damping coefficient of semi-active suspension can be generated when lateral car body motion and lateral relative (car body and bogie) motion are in the same direction. If the two states of a car body motion and a relative motion are in the opposite direction, the damping coefficient is generated as a minimum value as shown in (2):

\[
C_{\text{desired}} = \begin{cases} 
C_{\text{sky}}, & \text{if } v_c (v_c - v_b) > 0 \\
C_{\text{min}}, & \text{if } v_c (v_c - v_b) \leq 0 
\end{cases}
\] (2)

Where \(F_d\) is a damping force which is generated in the lateral damper.

This paper proposed a skyhook control strategy for the semi-active damper to reduce lateral motion of a railway vehicle on an irregular track.

B. Observer design

The velocities can be obtained by an observer. The estimation error is not affected by unknown external disturbances. The observer can be expected to perform better when sensor noise is small relative to the disturbance input and the sprung mass and unsprung mass velocities cannot be estimated using deflection acceleration measurements [12], [13].

In order to apply the control algorithm, lateral accelerations of a car body and bogie are observed. Lateral velocities of a car body and bogie are calculated using the observed acceleration. The velocities are applied to a controller, and a damping coefficient, which is the control gain, is calculated by the controller. The damping constant is determined as shown in (1).

In order to observe velocities of a car body and bogie, a quarter-car model was developed. A railway vehicle can be split into quarter-car suspension models, and one quarter-car model is described in Fig. 2 which was considered for observer design. The spring, a variable damper, a quarter of the car body mass, half the bogie mass and the wheel-set constitute the quarter-car model. Wheel behavior is locked to track irregularities. So, the wheel is modeled as a spring but its mass and damping characteristics are assumed to be negligible [14].

The state space model of the semi-active suspension is modeled as the following quarter-car system:
Subtracting (7) from the actual state dynamics as shown in (4), we obtain the closed loop state observer:

\[
\dot{x}(t) = Ax(t) + Bu(t) + \varepsilon(t)
\]

where \( L \) is the state estimation feedback gain or the observer gain matrix, and \( \varepsilon(t) \) is the output estimation error as follows:

\[
\varepsilon(t) = y(t) - \hat{y}(t) = Cx(t) - C\dot{x}(t) = Ce(t)
\]

where the state estimation error is defined as:

\[
e(t) = x(t) - \hat{x}(t)
\]

and the closed loop estimation error dynamics can be written as:

\[
\ddot{e}(t) = A(x(t) - \hat{x}(t)) - LC(x(t) - x(t)) + \Gamma\dot{e}(t) - Le(t) = (A - LC)e + d(t)
\]

The estimated lateral velocity of a car body is compared with the actual lateral velocity as shown in Fig. 3. The state observer is further described by the block diagram in Fig. 4. In order to input the state into the controller, the lateral velocity can be estimated by the observer, which is illustrated in the dashed line shown in Fig. 4.

III. DYNAMICS MODEL OF A RAILWAY VEHICLE

A. Railway vehicle model

This section discusses the full scale MBS model of a railway vehicle. In this paper, dynamic characteristics of a current high-speed train were applied to an MBS (Multi-Body System) simulation tool. Multi-body dynamic analysis was implemented using the numerical model of a railway vehicle. Fig. 5 shows a rail vehicle that was developed for maximum speeds of 430km/h on tangent track and 370km/h on curved track.

The suspension system affects running safety and ride stability of the railway vehicle. The suspension is divided into a primary suspension system and a secondary suspension system. A bogie model was applied to a primary suspension and a secondary suspension. The primary suspension consists of a coil spring and a vertical damper. The secondary suspension consists of an air spring, a vertical damper, a yaw damper and a lateral damper. Various design parameters such as spring characteristic and damping coefficient were applied to the railway vehicle model. A Z-link connects a vehicle’s body and a bogie. The Z-link is a center-pivot which was implemented as a kinematic structure. The bogie model is shown in Fig. 6.

B. Wheel/rail and track model

The objective speed of a high speed train is 370km/h on curved track and 430km/h on tangent track. Hence, the simulation was implemented at these speeds with track irregularities. The lateral irregularity and the vertical irregularity of the track are shown in Fig. 7. The curvature of the track is 1/7000m, the cant is 130mm and the transition curve is 400m.

The S1002 wheel and the UIC 60 rail were adopted in the railway vehicle model. The wheel profile and rail profile are shown in Fig. 8.
A. Model validation

Before the simulation, in order to validate the numerical model, the model was experimentally validated by roller-rig tests. The high speed train is underdeveloped and the roller-rig test is performed by a single car of the train before field test for stability and safety. The test method involves the railway vehicle set on a roller rig, and a roller is rotated to run the vehicle on the rollers using a motor. A railway vehicle is excited by yaw motion of the roller at some velocity of a railway vehicle. The excitation amplitude is 0.2 deg and the excitation frequency is 6Hz.

The stability of the vehicle was evaluated by rig test. The test results and simulation results are shown in Fig. 9, which is for a vehicle speed of 370km/h. The RMS values of the car body lateral acceleration in the test and simulation results are 0.21 and 0.25 m/s², respectively. The maximum values of the car body lateral acceleration in the test and simulation results are 0.56 and 0.60 m/s², respectively. The RMS values of the bogie lateral acceleration in the test and simulation results are 0.75 and 0.67 m/s², respectively. Also, the maximum values of the bogie lateral acceleration in the test and simulation results are 1.43 and 1.48 m/s², respectively.

B. Result of multi-boy system simulation

Simulations were performed in MATLAB/Simulink and ADAMS/Control to investigate the performance of lateral behavior and ride comfort. For the skyhook damping coefficient, the maximum value of $C_{sky}$ is set to 30kNs/m and minimum value of $C_{sky}$ is set to 10kNs/m. Ride comfort is measured by evaluating the accelerations in the car body, divided into front, middle and rear bottom sections. The evaluation method of the ride comfort that was used is UIC 513 (using the mean comfort standard method) [15]. The results of ride comfort evaluation are shown in Figs. 10-11. The Fig. 10 is the results on tangent track, and the Fig. 11 is the results on curved track.

In the Fig. 10 and Fig. 11, ride comfort of the railway vehicle is more improved by the performance of the semi-active suspension system than the passive suspension system. Also, you can see that the ride comfort index at the rear car body is more improved than in other sections.
V. CONCLUSION

The objective of this paper has been to examine the use of a state observer system with a skyhook control algorithm for improving the safety and stable lateral behavior of a railway vehicle.

In this study, two models were developed: a quarter-car and MBS model. In order to secure the reliability of the developed MBS model, a roller rig test was implemented by a single car, and the simulation results were compared to the roller rig test results. It was shown that the lateral state can be estimated by the proposed observer design. The performance of the skyhook control system was compared with the passive system in dynamic analysis on the irregular track, and simulation results show that ride comfort is more improved using the semi-active system compared to the passive system. We can conclude that the semi-active system guarantees better performance than the passive one. As future work, the high speed train semi-active suspension will be tested on real track.

REFERENCES