Semi-Active Control Method for HSR-350x

Sang-Soo Kim, Young-Guk Kim, Young-Jae Han and Choonsoo Park

Korea Railroad Research Institute, Uiwang, Korea

Abstract
Now a day, passengers require reliable stability and high ride comfort to the high-speed rolling stock. Therefore, previously used passive suspension is required to be changed to high accuracy and reliable performance one. Meanwhile, improvement of velocity and ride comfort is influenced by vibration which is generated by rail irregularity and passing tunnel. To reduce these vibration, several vibration control method has been considered to be applied on rolling stock. In this paper, we adopted semi-active control using sky-hook system. HSR 350x is the first high-speed test railway developed by Korean technology. And HSR 350x is tested on the high-speed line using semi-active suspension during running.

Introduction
Since 2004, KTX has been commercially operating and achieving elevation on transport capacity in the business report. Now a day, passengers require reliable stability and high ride comfort to the high-speed rolling stock. Therefore, previously used passive suspension is required to be changed to high accuracy and reliable performance one. Meanwhile, improvement of velocity and ride comfort is influenced by vibration which is generated by rail irregularity and passing tunnel. To reduce these vibration effects, active suspension has been suggested and applied on rolling stock. Thus many companies and institutes are making effort for researching the active suspension for train.

Now, the HSR350x which was developed by R&D project for Korean Hi-Speed Railway of Ministry of Construction & Transportation, is trial running on Kyung-bu high-speed line, and achieved 350km/h on increasing speed test in 2004, the forth attainment in the world. The ride comfort elevation technique of trailer car is required as train speed increase.

In this paper, we suggest the installation of semi-active lateral dampers to improve ride comfort of HSR350x. HSR 350x was constructed in 2002 at the maximum speed of 350km/h. And it is composed of 7cars; 2 Power Cars, 2 Motorized Trains and 3 Trailer Trains. We suggest lateral vibration control at the mounting lateral suspension between car body and the bogie in Power car. To compare the behaviors of the train in cases of the application and no application of the semi-active dampers easily, we have installed the lateral vibration control suspension to 1 Power car. We adopt the control method as sky hook control. It uses the virtual wall along to the car body and the damper that is installed between the car body and the virtual wall generated the damping force according to the velocity of the car body. The virtual wall and the damper do not exist in real system and the conventional damper was installed between the car body and the bogie and it generates the damping force according to the relative velocity of the car body and the bogie. So we need the special damper, which can change the damping coefficient easily. To utilize this sky hook control method, lateral semi-active suspension and two accelerometers should be mounted on both ends of the power car (TP1). Semi-active suspension consists of two dampers those have variable damping coefficients. The absolute velocity of the car body is calculated the accelerometers. Then the controller calculates the sky hook damping force using the absolute velocity of the car body and changes the damping coefficients of the semi-active dampers. If the sign of the relative velocity between the car body and the bogie is equal to that of the velocity of the car body, the semi-active dampers generate the sky-hook damping force changing the damping coefficients. Otherwise the dampers hardly produce damping force and avoid the opposite directional force.

The conventional passive dampers of the power car (TP1) were replaced to the semi-active dampers. The running test using semi-active control was performed during the test run on the high speed line. And the results show better performance using suggested system.

Characteristics of semi-active suspension
The sky-hook system was devised by Karnopp in 1972 [1]. The principle of sky-hook system is depicted in Figure 2(a). The upper figure is the scheme of the passive damping system and the lower figure is that of the sky-hook damping system. Compared to the passive damping system, the damper
is connected from the mass to the sky at the sky-hook damping system. Hence the damper generates the damping force proportion to the absolute velocity of the mass. Thus the damping force, \( f \), becomes as Eq. (1)

\[
\begin{align*}
\begin{cases}
  f = C_d(V_b - V_o) & \text{(passive damping system)} \\
  f = C_s V_b & \text{(sky-hook damping system)}
\end{cases}
\]

where \( C_d \) is damping coefficient of passive damping system, \( C_s \) is that of sky-hook damping system, \( V_b \) is the velocity of the car body and \( V_c \) is the that of wheel respectively.

The comparison between the passive and the sky-hook damping system is shown in the Figure 2(b). The upper figure is the frequency response of the passive damping system and the lower figure is that of the sky-hook damping system. X-axis is the frequency ratio coordinate and y-axis indicates magnitude ratio (transmissibility). At the passive damping, if the damping ratio, \( \zeta \), is increased, the transmissibility is decreased at the resonant but the transmissibility is increased at high frequency region. However for the sky-hook damping system, the transmissibility is significantly lower than that of the passive damping system at all frequency concerned if the damping ratio is increased.

\[
\begin{align*}
\begin{cases}
  f = C_s V_b = C_G (V_b - V_o) & \text{(sky-hook damping system)} \\
  f = 0 & \text{(passive damping system)}
\end{cases}
\end{align*}
\]

(2)

For the sky-hook damping system, the rigid ceil connected with damper is imaginary wall. Thus fot practical implementation, the principle of the sky-hook damping can be realised by the arrangement shown in Figure 2. The feedback measurement is provided from the sensor mounted on the car body and the control demand is fed to the actuator which is placed between the carbody and the wheel [2].

In this paper, authors adoted the semi-active suspension of which the damping force can be generated close to that of the sky-hook system written in Equation (2) where the \( C_G \) is the controlled damping coefficient of the semi-active suspension. \( C_G \) must be variable according to the relative velocity \((V_b-V_o)\).
The problem is how the damper with variable damping coefficient can be realized. KYB industry developed the hydraulic damper with variable damping coefficient and applied to Japanese high-speed railway (Shinkansen) shown in Figure 3.

The authors designed the damping characteristics of the semi-active damper shown in Figure 4. The damper is operated in two modes. The first case is the semi-active damping mode following the Equation (2) and the other case is the passive damping mode while the controller or the sensors does not work. The violet line indicates the passive damping mode while the controller or the sensors does not work. The damper cannot generate the zero damping force because of the structure of the damper. The damper has minimum damping characteristics as the black line during the second case of the Equation (2).

Two dampers are manufactured and the test results of the damping characteristics are shown in Figure 5. The dampers have good quality with the designed value.
Mounting semi-active suspension on HSR 350x

The national project for development of Korea High Speed Train has been conducted for 6 years and the prototype high speed railway named HSR 350x was constructed in 2002 at the maximum speed of 350km/h shown in Figure 6. HSR 350x is composed of 1set for 7cars, 2 Power Cars, 2 Motorized Cars, 3 Trailer Cars developed by own Korean technology. Now it has been trial running on the Kyoung-bu and Honam line under reliability research.

Trailer cars have no lateral damper and the authors researched lateral vibration control as mounting lateral suspension between car body and bogie in Trailer car. The results showed the 15% better riding comfort using the optimized lateral damper [5].

In this paper, we suggest the installation of the semi-active suspension to Power car (TP1) to increase the riding comfort of HSR 350x. Figure 7 (a) shows the arrangement of the semi-active suspension system. Two dampers are replaced with semi-active dampers per each bogie and the accelerometers are attached in the car body. The signals are inputted to the controller and the semi-active suspension generates damping force following the sky-hook control method shown in Figure 7 (b).
Using sky-hook control method, if lateral external force $F$, caused by train crossing and rail irregularity, is applied on the train, the system operates the lateral vibration control. The absolute velocity of the car body is calculated by the integration of the signals of accelerators located at both ends of the power car (TP1). The controller, which is suggested by semi-active suspension, utilizes sky-hook algorithm to generate damping force that is proportion to absolute velocity of car body and equal value damping force at the damper located between bogie with car body. The characteristics of semi-active suspension are shown in Figure 8. Case (a) is the passive damping mode. The black line is the absolute velocity and red line is the damping wave. The system has damping force proportion to the relative velocity between the car body and the bogie. On the other hand case (b) is the semi-active damping mode. If the sign of the car body velocity and the relative velocity is identical, the system generates the damping force. Otherwise if the sign is not identical, the damping force becomes minimized.

Running test of HSR 350x

HSR 350x equipped with semi-active suspension was tested in Korean high-speed line over 300km/h. The semi-active control was performed in real running test. The sky-hook damping coefficient, $C_s$, is set to 400kN/(m/s). The train first ran through the test region in passive damping mode and ran again the same test region in semi-active damping mode with same running condition including velocity 300km/h.

And the test power car (TP1) was proceeding during the test. The test results are shown in
Figure 9. The uppers are the acceleration responses of the front part of the car body and the lowers are those of the rear part. Y-axis indicates the acceleration [m/s²] and x-axis is the test time [sec]. The peaks around 5700s of damper 1 and 5620s of damper 2 shown in Figure 9 (a) are decreased using semi-active control shown in Figure 9 (b).

The frequency responses of time responded are analyzed and are shown in Figure 10. Figure 10 (a) is the result of the passive control and Figure 10 (b) is the result of the semi-active control, the left is the front side response and the right is the rear side response of the car body. In the front side, the two resonant peaks are decreased significantly and the response of higher frequency region is deceased two using the suggested control method. In the rear side, the second resonant peak is decreased with semi-active control.

![Figure 9. Time response](image1)

![Figure 10. Frequency response](image2)
Conclusion

In this study, the authors suggested the semi-active lateral control method for Korean high-speed railway and tried the semi-active suspension system to 1 power car of HSR 350x to improve the riding comfort. The results are following:

Semi-active suspension was installed to HSR 350x successfully and tested on high-speed line.
Using suggested system, it is confirmed the lateral acceleration of car is decreased than passive control mode.
Also, we expect the riding comfort becomes better because of the decrease of the lateral acceleration. This research will be continued and the characteristics of this system will be revealed more detail through several running condition.

Acknowledgements

The authors gratefully acknowledge that this research is supported by System engineering projenct of Technology development for Next generation high speed railway system from Korean Ministry of Construction & Transportation.

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