# Semi-active Suspension System

# for the Yamanashi Maglev Vehicles

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**Abstract**

In order to improve the ride comfort of the Yamanashi Maglev vehicles, a semi-active suspension system to control lateral vibrations of the vehicle (lateral control) was designed. In 1999, adjustable damping force dampers (adjustable dampers), accelerometers of the car body that can function properly in magnetic fields, and semi-active controller for the Maglev vehicle were developed. Vehicle-running tests on the Yamanashi Maglev Test Line confirmed an improvement of 3 dB in the lateral ride comfort. Although an improvement in the lateral ride comfort was detected by human perception, the vertical vibrations were perceived to be strong. In 2001, work commenced on the development of a semi-active suspension system to control vertical vibrations (vertical control). Characteristics of this vertical control are being confirmed in vehicle-running tests. An improvement of 2 dB was confirmed so far. This paper describes an overview of the application of the semi-active suspension system on the vehicles of the Yamanashi Maglev Test Line, and the results of vehicle-running tests.

## 1 Introduction

The ride comfort of the Maglev vehicles is disturbed by vibrations transmitted from the bogies, caused by irregularities in the alignment of the coils attached to the side walls of the guideway. The ride comfort is also influenced by aerodynamically-generated vibrations of the car bodies. Higher vehicle speeds result in worse ride comfort. The Yamanashi Maglev vehicles are different from those of conventional railway systems by features such as the following. The Maglev vehicles:

(1) are supported by magnetic forces between the bogies and guideway.

(2) run at 500 km/h on the ground.

(3) have articulated bogies.

However, the mechanisms that cause the ride comfort to worsen are the same.

If a stationary virtual wall existed on one side of a car body, and an imaginary damper could be fixed to this wall, it is possible to reduce car body vibrations without the vibrations being transmitted from the bogie. This imaginary damper is called a sky-hook damper. There are two methods for supplying energy as the sky-hook damper. The first method uses hydraulic actuators in a full-active suspension system, and the second method uses adjustable dampers in a semi-active suspension system. A full-active suspension system can theoretically realize favorable characteristics. However, it would consume enormous energy and therefore require a large power source, meaning that this system might be large and heavy in weight. A semi-active suspension system, which adjusts the damping forces corresponding with the vibrations of the car body, can realize nearly the same characteristics as that of the full-active suspension, while being low in energy consumption, simple in structure, and light in weight. Therefore, a semi-active suspension system was selected to be developed for the Maglev vehicles.

## 2 Semi-active suspension system

### 2.1 Components of the semi-active suspension system

Fig. 1 shows the components of the semi-active suspension systems for Maglev vehicles. Lateral and vertical control systems are described. The components consist of adjustable dampers set between car body and bogie, and accelerometers and controllers set in the car body. It is a simple system. In the lateral control, two adjustable dampers are set horizontally at centers of the end beams. In the vertical control, four adjustable dampers are set vertically on the end beams near the corners.

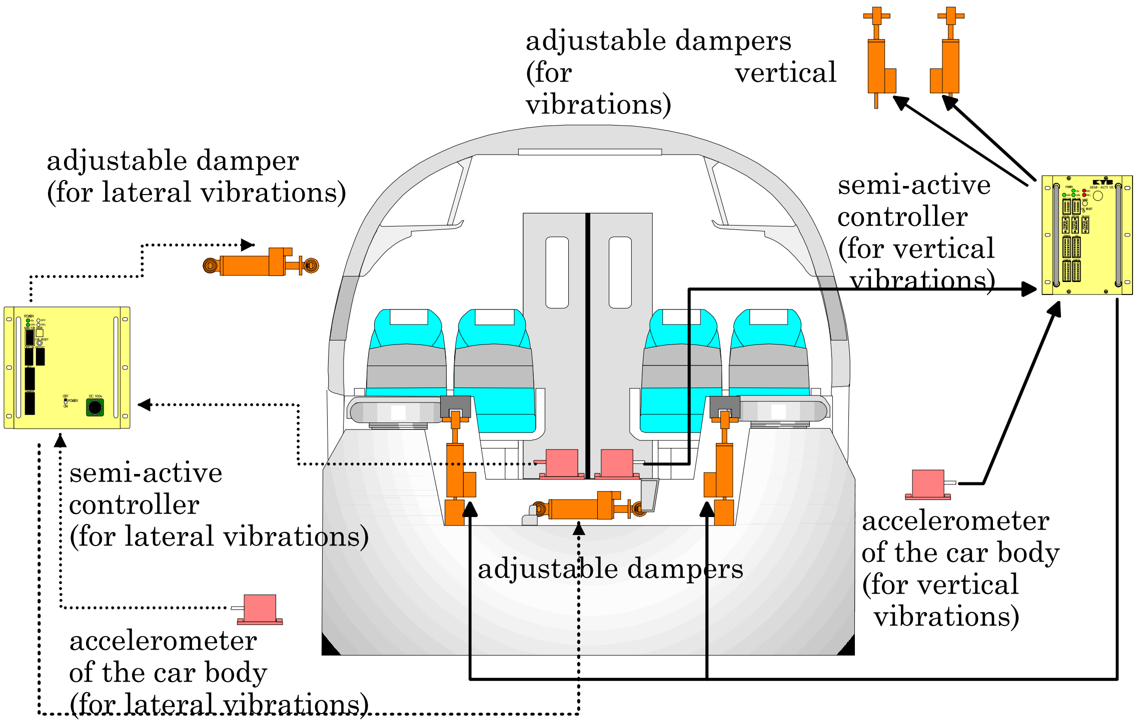


Fig. 1 Components of the semi-active suspension system

### 2.1.1 Adjustable dampers

Adjustable dampers are set between the car body and bogie, and generate damping forces corresponding with vibrations of the car body. As they are set between the car body and bogie, the dampers must function properly in magnetic fields. Two kinds of adjustable dampers, one kind using a high-speed solenoid valve system and the other using a proportional relief valve system, were tested in strong magnetic fields. Based on the test results, the proportional relief valve system was selected for application. Fig. 2 shows the structure of the adjustable damper using a proportional relief valve system.

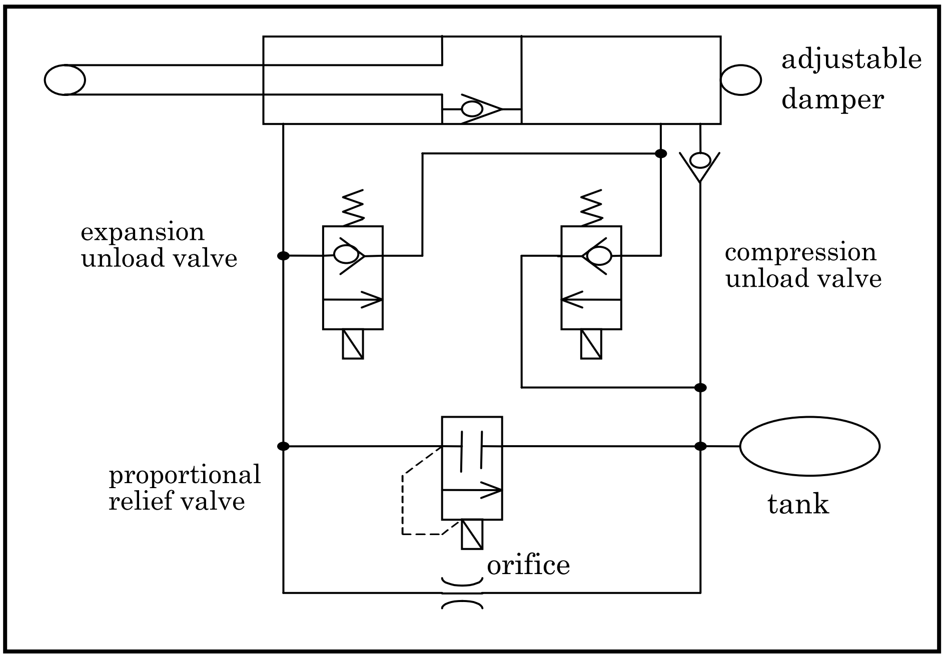


Fig. 2 Structure of an adjustable damper using a proportional relief valve system

### 2.1.2 Accelerometers

Accelerometers are set in the car body. They measure the vibratory accelerations of the car body that are integrated to vibratory velocities, used by the controller to determine the damping forces. If the transmission of these signals to the controller stops, the controller assumes that the acceleration is zero. Therefore, the controller would continuously output the least damping force. To avoid this abnormal situation, the accelerometers of the semi-active suspension system must have fault-diagnosis capabilities. When the diagnosis recognizes the fault, the controller will stop controlling the system, and the adjustable dampers will act as if they were passive dampers in changing the damping forces.

### 2.1.3 Controllers

The controllers receive the vibratory accelerations of the car body and integrate them to obtain vibratory velocities of the car body. The controllers dictate damping forces corresponding with the magnitudes and directions of the velocities. According to sky-hook damper theory, it is necessary to use negative damping force. However, it is impossible for the dampers to generate actual negative damping force. In this situation, the damping force is set to zero using unload valves. The controllers also have fault-diagnosis capabilities in order to avoid abnormal situations as described in the previous section, 2.1.2. It is a fail-safe system.

## 3 Results of the semi-active suspension system in vehicle-running tests

### 3.1 Evaluation of ride comfort

In this paper, the ride-comfort level is used to evaluate the effectiveness of the semi-active suspension system. The ride-comfort level $L_T$ (dB) is defined as follows:

$$L_T = 10\log_{10}\left(\frac{\overline{a}^2}{a_{ref}{}^2}\right)$$

Here,

$\overline{a}$ : Root mean square of weighted acceleration of car body (m/s$^2$)

$a_{ref}$ : Reference acceleration ($10^{-5}$ m/s$^2$)

To calculate weighted acceleration of car body, the frequency weighting curves for lateral and vertical vibrations are used, as shown in Fig. 3, which is based on ISO-2631.

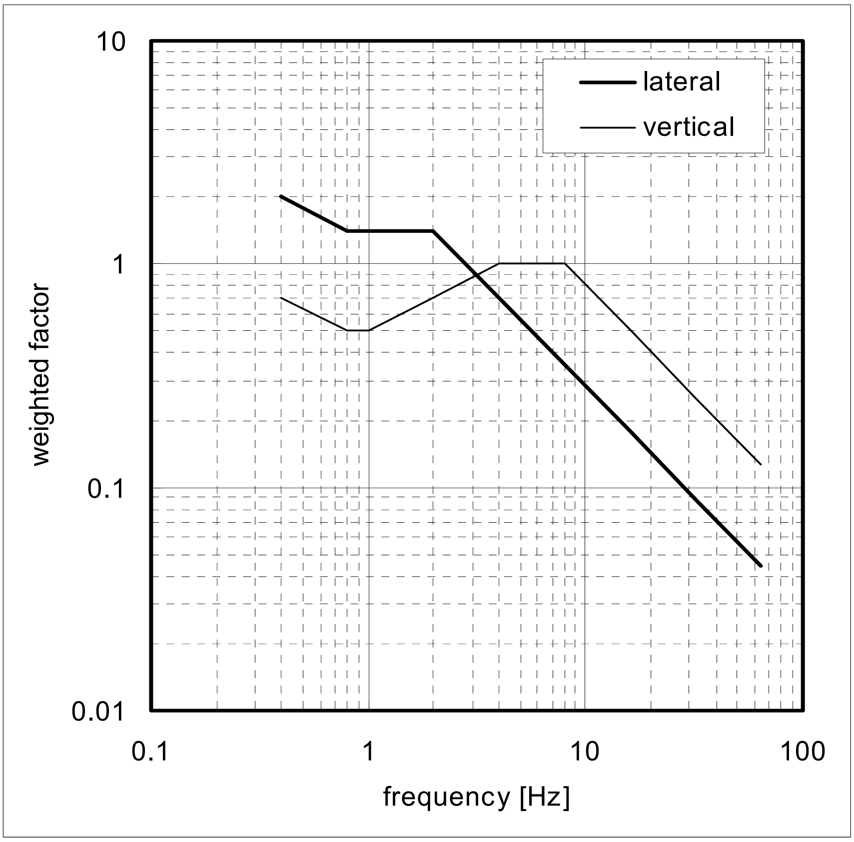


Fig. 3 Frequency weight curves for ride comfort

### 3.2 Results of the lateral control

In 1999, the lateral semi-active suspension system was set up in the Yamanashi Maglev Test Line vehicles, and vehicle-running tests were carried out. Vehicle-running tests using this lateral control produced the following results:

(1) The short-time lateral ride-comfort level was improved by 2 to 5 dB and the average lateral ride-comfort level was improved by 3 dB.

(2) The PSD is reduced for frequencies of 3 Hz or less.

(3) The improvement in the lateral ride comfort was detected by human perception.

The reduction of the PSD resulted in an improved assessment of ride comfort because human perception is particularly sensitive to vibration frequencies of 2 Hz or less.

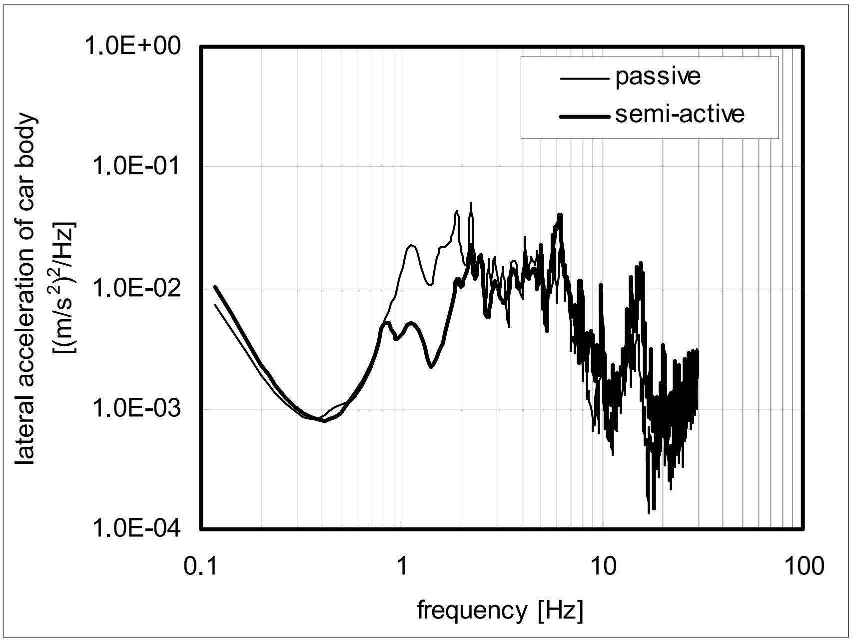


Fig. 4 PSD analysis of lateral accelerations of the car body

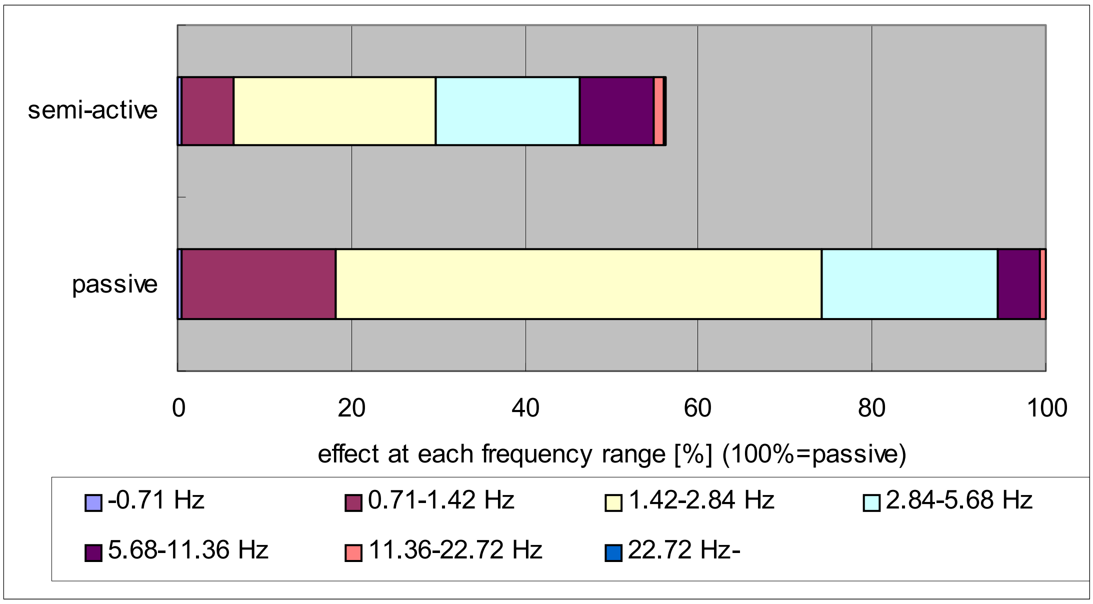


Fig. 5 Effect of lateral control at each frequency range

Fig. 5 shows effect of lateral control at each frequency range. With lateral control, lateral accelerations of frequencies of 3 Hz or less were reduced substantially.

### 3.3 Results of the vertical control

In 2001, the vertical semi-active suspension system was set up in the Yamanashi Maglev Test Line vehicles, and vehicle-running tests were carried out. In the initial stages of design by control theory, the car body was considered to be rigid, as in the lateral control. However, semi-active damping forces induced flexural vibration (first bending mode) of the car body and no improvement of vertical ride comfort was confirmed.

The flexibility of the car body was considered next in the vertical vibrations, and flexural elements were added to the vibration modes of vehicle dynamics. The accelerations of the vertical vibration mode, pitching mode, and flexural vibration mode were integrated and processed using sky-hook damper theory. The damping forces were calculated by adding each mode order linearly.

With this new control, the short-time vertical ride-comfort level was improved by 2 dB. The PSD is lower for frequencies of 3 Hz or less.

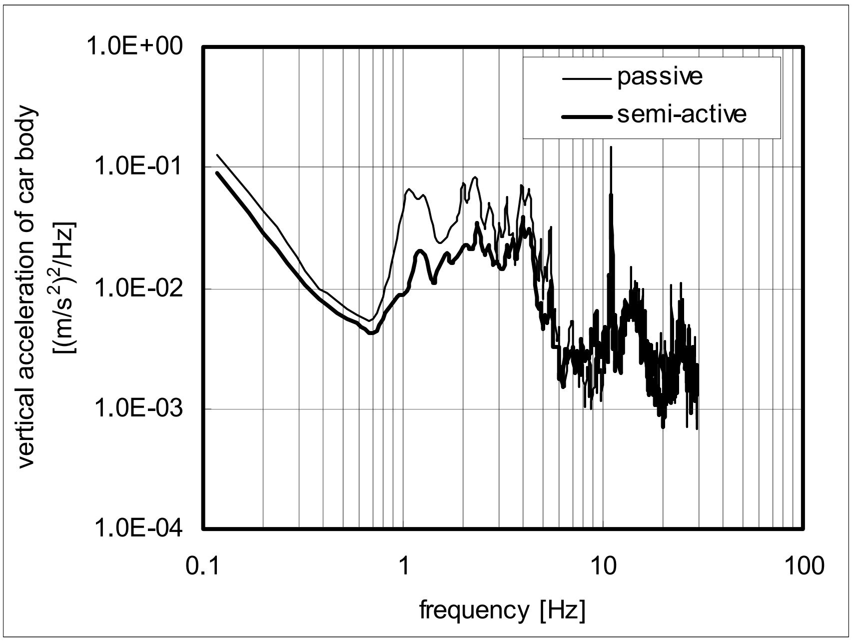


Fig. 6 PSD analysis of vertical accelerations of the car body

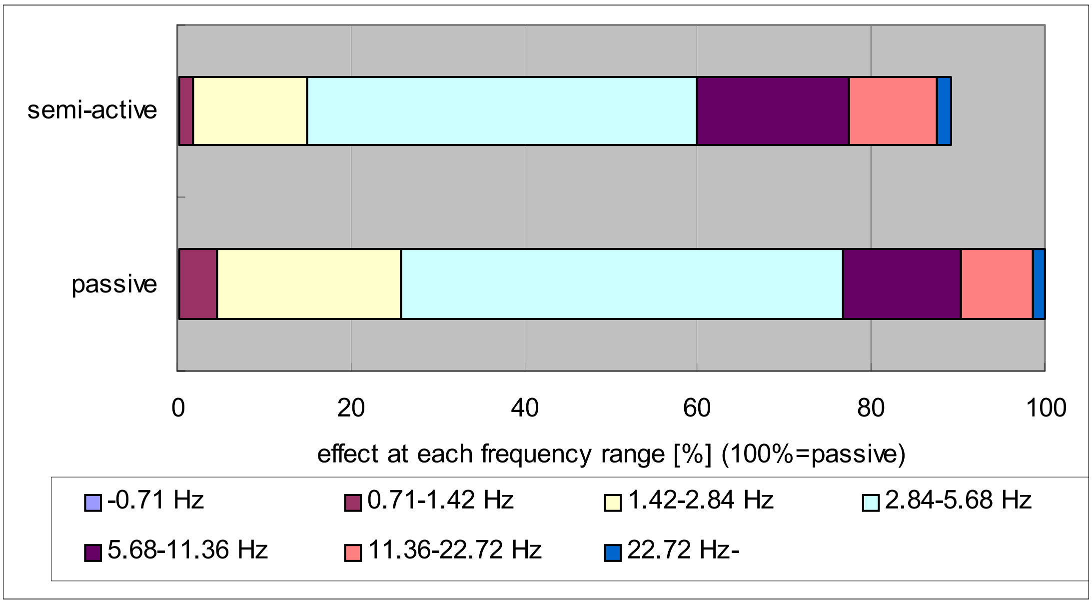


Fig. 7 Effect of vertical control at each frequency range

Fig. 7 shows effect of vertical control at each frequency range. With vertical control, vertical accelerations of frequencies of 3 Hz or less were reduced substantially.

## 4 Conclusions

The semi-active suspension systems for Maglev vehicles were developed, and the following results were obtained:

(1) A lateral semi-active suspension system was developed, and an improvement of 3 dB in the average lateral ride-comfort level was confirmed in vehicle-running tests.

(2) A vertical semi-active suspension system is being developed, and an improvement of 2 dB in the short-time vertical ride-comfort level was confirmed in vehicle-running tests.

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