A Lateral Semi-Active Suspension of Tilting Train

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To improve train ride quality, a lateral semi-active suspension has been developed and subjected to a running test. Typical tilting trains of Japan have too small resistance in their tilting mechanism to apply this semi-active suspension system.

To make an effective semi-active suspension, a changeable tilting damper has been developed and tested with semi-active suspension.

As a result, the following have been verified. (1) The semi-active suspension without changeable tilting damper suppresses the lateral vibration of carbody about 20–30%. (2) Its performance becomes worse at the end of a traverse curve. (3) The changeable tilting damper improves the performance of semi-active suspension. (4) Using both semi-active suspension and changeable tilting damper is an effective way to improve the ride comfort of tilting trains.

Keywords: Semi-active suspension, Tilting car, Changeable tilting damper

1. Introduction

High-speed operation of trains brings new vibration modes that cause aerodynamic forces. For example, aerodynamic lateral vibration increases on Shinkansen trains in tunnel sections. This vibration appears strongly on the cars that have current collectors or the tail car of trains.

Traditional suspensions have been designed to reduce the vibration that causes track irregularities. So, these suspensions are required to "isolate" the truck vibration and set to small damping and soft springs.

But because of the aerodynamic force that works directly on the carbody, a great damping force is required to reduce the aerodynamic vibration.

This means that the best suspension setting of isolating truck vibration and reducing aero-dynamical vibration will be incompatible.

So, it is difficult to set the best parameters to both vibration modes on the traditional suspensions.

New series Shinkansen trains (e.g. 500-series, 700-series) have semi-active suspension systems as a solution to this problem.

In the fields of narrow gauge trains in Japan, it has been thought that the aerodynamic vibration is not important because of its low maximum running speed of about 130 km/h. But recently it is known that the aerodynamic force brings large lateral vibration similar to that of the Shinkansen train in single track tunnels. This increase of vibration is remarkable on tail cars of high speed tilting trains. Most Japanese tilting trains have a small resistance on the tilting mechanism. So, the tilting train is sensitive to the force that works directly on the carbody. This paper describes a way of reducing lateral vibration of the tilting train by using semi-active suspension and changeable tilting dampers.

2. Configuration of the tested system

2.1 Tilting system

Tilting cars (trains) can compensate for the centrifugal acceleration, which is uncomfortable for passengers due to the tilting motion of the carbody.

Fig. 1 shows the most popular tilting mechanism in Japan. On this tilting system, the carbody is set on tilting beams, which are guided by linear bearings. The motions of the beams are restricted to the circumference of the circle around the tilting center. A tilting actuator and a tilting damper are installed between the truck frame and tilting beam.

Because of this circular motion, the rise of mass-center, which is related to the tilting motion, is very small.
So, this tilting mechanism can tilt with a smaller operating force than that of a link type tilting mechanism. This type tilting train can get some degree of compensation by the tilt angle caused by the centrifugal force of the carbody. However, if there are no tilting actuators, the tilting mechanism has a large response time. Lagged response causes low frequency acceleration in traverse curves. Furthermore, without the actuator, low frequency vibrations will often occur. So, some passengers will get motion sickness.

To improve this situation, a tilt control system is installed. In this system, the controller has a track database. Counting pulses of the odometer, which is installed on the wheel axle, determines the train location. Automatic Train Stop system (ATS) coils, which are set on the track, are used as the reset points of the location of running train.

To prevent a quick movement of the tilt beam, a tilting damper is installed between the truck frame and tilting beam.

This type of tilting mechanism can move by small force. However, this type of tilting mechanism is sensitive to the forces that directly work on the carbody (e.g., aerodynamic force, centrifugal force). Furthermore, the pneumatic actuator has a large compliance, and when the tilting velocity is small, the damping coefficient of the tilting damper is also small. As a result, this type of tilting train has a property that aerodynamic forces in tunnels create a lateral vibration on the carbody of this tilting train.

2.2 Semi-active suspension

Semi-active suspension is a way of suspension control that improves the ride comfort by the control techniques similar to active suspensions. But the semi-active suspensions reduce the vibration by controlling parameters of suspension, such as damping-coefficients, instead of using external energy.

So, this is different from an active suspension because the semi-active suspension does not require any power source (e.g., air compressor, hydraulic pump). From this point of view, this type of suspension, which reduces vibrations by dynamic control of parameters, is called a “semi-active” suspension.

A semi-active suspension has the following characteristics that suit railway vehicles.

(1) Semi-active suspension is effective for both aerodynamic vibrations and normal vibrations, which are caused track irregularities. Especially, this system can reduce the vibrations of resonant frequency of car the body.

(2) Semi-active suspensions always behave as dampers. So the semi-active suspension systems have the advantage of stability in comparison with active suspensions. This means that backup systems for troubles of semi-active suspensions become simple.

(3) Because no power source is required, the sets of semi-active suspensions can be made to be compact.

Fig. 2 shows the semi-active suspension system of the tilting train. Changeable lateral dampers are installed between the carbody and tilting beams. Two lateral acceleration sensors are also set on the carbody, which detect the vibration of the carbody at the truck center. The controller assigns damping force of the changeable dampers to reduce the carbody vibration.

2.3 Changeable dampers

Fig. 3 shows the changeable lateral damper structure of the high-cycle solenoid valve type. And Fig.4 shows the structure of the electrically controlled reducing valve type. When power is not supplied, both types of changeable dampers work as passive dampers.

The changeable damper in Fig. 3 is in practical use on Shinkansen trains. This damper has a piston speed...
detector. The controller refers to the piston speed, then selects an optimal combination of valves to get necessary control force under the condition of detected piston speed.

The merits of this type are as follows:
(1) Small changing delay of damping force.
(2) Wide range of changeable damping coefficient.
(3) High reliability valve system. This type of valve is able to resist contamination from hydraulic fluid.

Because of these merits, the first trial system was designed with this type of changeable damper. But this type of changeable damper is expensive. So, From the viewpoint of costs, it seems difficult to apply this changeable damper to practical use on narrow gauge trains.

The changeable damper in Fig. 4 was developed with a cost-down objective. This damper controls the damping force by an electrically controlled relief valve regardless of piston speed. So, the (expensive) piston speed detector is omitted. The number of parts of this damper is reduced.

In the case of power down, this damper must behave the same as the original passive damper. So, the characteristic of this damper against valve current is as shown as Fig. 5.

The “unload valves” of these dampers select the direction of damping forces. These valves cut the damping force of compressed or extended directions. If the two unload valves open at the same time, damping force will be too small. This is a very dangerous situation on the running stability of the train. So, an interlock circuit is installed to the valve driver.

2.4 Control algorithm

The control algorithm of this system is the “sky hook damper”. Fig. 6 shows the concept of the sky hook damper.

An actual lateral damper is installed between the carbody and truck frame. This damper reduces the vibration of the carbody, but at the same time, it conveys the vibration of the track frame to carbody. So, hard dampers are not always good to reduce the vibration of carbody.

If there is an immovable wall side in the car, the hard damper, which is installed between the wall and carbody will not convey “wall vibration” and shows very good performance for reduction of carbody vibration. It is impossible to get such a wall and damper in reality, but it is possible to get a similar force as an imaginary damper, which is installed between the wall and carbody by a controlled actuator that is installed between the truck and carbody. Because the damping force of the imaginary damper is in proportion to the absolute velocity of the carbody, an equivalent damper of the imaginary damper can be realized by controlling the actuator with absolute velocity of the carbody.
Such a control system is called the “sky hook damper”. This is a simple and effective control law. The sky hook damper decides the control force with absolute velocity of carbody independently of truck conditions. So, it is disadvantageous for truck stability. But the semi-active suspension system behaves as a damper, and its damping coefficient is always positive in contrast to the active suspension that often shows a negative damping coefficient. It means that the semi-active suspension does not ruin the stability of the truck. So, we select the sky hook damper as the control law of this system.

The ideal force of the sky hook damper is decided independently of truck vibration. But, the direction of created force of a semi-active system depends on the direction of piston speed. In other words, the control force of the semi-active suspension is influenced with the velocity of the truck. So, it is impossible to realize the complete sky hook damper by the semi-active system.

But, because the frequency of the track vibration is higher than that of the carbody, it is possible to create the force which is not far off the ideal sky hook damper by relieving the damper force which is in the direction of the absolute velocity of carbody.

Fig. 7 shows an example of the bench test for a changeable damper. For this test, the changeable damper is driven at a constant frequency and amplitude by an external actuator.

The forces of the changeable damper appear like the teeth of a comb, and this moving average corresponds to the command value. This shows that the control force can be created independently of truck vibration, and the semi-active system can realize a sky hook damper, in low frequency range.

Fig. 8 shows a block diagram of this control system. This system works on 10 ms of sampling rate. A digital filter calculates the lateral absolute velocity of car body by integrating the acceleration signal of carbody. Then the controller calculates the control force and sends a drive current to changeable damper. The lateral acceleration includes some centrifugal acceleration. So, in curve sections, a large drift appears in its integration (absolute velocity). Because this drift worsens the performance of reducing vibration, it is necessary to remove the drift. In this system, this drift is removed with moving average of absolute velocity and the frequency characteristics of the digital filter (integrator).

### 2.5 Changeable tilt damper

In the Fig. 1, a “tilt damper” is installed between the truck frame and tilting beam. This damper has very small resistance at low piston speed for smooth tilting motion. So, in the situations that the carbody directly receives external force (e.g. aerodynamic force in tunnel), the carbody moves with the tilting beam as one body. In this situation, the semi-active suspension, which is installed between carbody and tilting beam, can not suppress the vibration. If the tilting damper has large damping coefficient, this motion will be suppressed. In addition, the semi-active suspension, which is installed between the carbody and tilting beam, works well. But large damping coefficients of the tilting damper will restrict the motion of the tilting actuator.

Changeable tilting dampers have two solenoid valves, which raise the damping coefficients of the compression side or stretch side. These valves are switched in harmony with the tilt control system. Thus, the changeable tilting damper can suppress the motion of the tilting beam without hindrance to tilt control.

![Fig. 8 Block diagram of controller](image)

![Fig. 9 Effect of semi-active suspension without changeable tilting damper](image)

![Fig. 10 Effect of semi-active suspension with changeable tilting damper](image)
3. Running test

This system has been subjected to a running test. This test was implemented by using a 283 series train (diesel limited express train) of JR-Hokkaido. Fig. 9 shows an example of the effect of semi-active suspension without changeable tilting dampers. At the head of Fig. 9, the RMS of acceleration of lateral vibration is shown in five second intervals. In this figure, it is found that the semi-active suspension suppresses acceleration of lateral vibration by 20 ~ 30%. But at some points, the effect of semi-active suspension is not clear. These points mostly appear at the end of a traverse curve. Thus, it is supposed that the carbody moves with the tilting beam as one body by the force that directly works on carbody, so the semi-active suspension can not suppress the lateral vibration. A similar phenomenon is seen after entering a tunnel.

Fig. 10 shows the effect of semi-active suspension with changeable tilting dampers. It is found that the peak of vibration is decreased remarkably. The acceleration of controlled train decreases below one half the acceleration of traditional suspensions. This shows that using both semi-active suspension and changeable tilting damper is an effective way to improve the ride comfort of tilting trains.

4. Conclusions

A lateral semi-active suspension system of tilting train was reported. First, the typical tilting mechanism used in Japan and its characteristics were introduced. Second, the features of semi-active suspension and its components (changeable dampers, control system, changeable tilting damper) were explained. Lastly, this system was subjected to a running test. From the test, the followings were clarified:

(1) The semi-active suspension without changeable tilting damper suppresses the lateral vibration of carbody about 20-30%.
(2) Its performance becomes worse at the end of a traverse curve.
(3) The changeable tilting damper improves the performance of semi-active suspension.
(4) Using both semi-active suspension and a changeable tilting damper is an effective way to improve ride comfort of tilting trains.

Reference