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Technical Reports

Tilting Control System for Railway Vehicles Using Long-Stroke Air Spring

by

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Synopsis

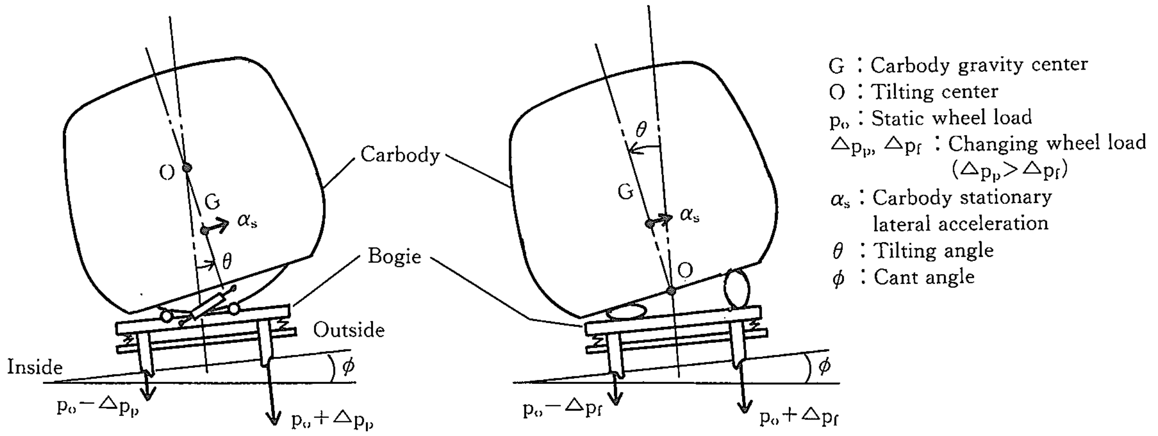
In cooperation with East Japan Railway Company (JR-EAST), a tilting control system for railway vehicles has been developed in order to attain speeds of 120 km/h curving velocity on 400 m radius curves. For the purpose of ensuring running safety and riding performance for accelerated curving, this system tilts a carbody up to a 7 degree tilting angle using two long-stroke air springs mounted on a bogie.

The system was installed in JR-EAST's narrow gauge experimental train and tried out on the running tests for curving speed. The test results showed that tilting control performance was successful. Consequently adequate running safety and good riding performance were verified, with the target curving velocity being achieved.

1. Introduction

Running speeds of railway vehicles have been increasing in order to reduce journey times. Especially on narrow gauge lines with many consecutive curves, raising the restricted curving velocity can reduce journey time more than an increase in the vehicle's top speed. For this reason, pendulum systems have been introduced in some expresses so that curving velocity can increase 20-30 km/h over the basic curving velocity restriction[1].

However, the greater the pendulum tilting angle, the more the carbody gravity center geometrically shifts to the outside of the curve as shown in **Fig. 1** and **Table 1**. This means the running safety margin on curves tends to be reduced. Therefore, the increase in curving speed using pendulum systems will soon reach its limitation. For the purpose of



An example of pendulum type

An example of forced tilting type

Fig. 1 Tilting situations of pendulum type and forced tilting type

Table 1 Comparison between pendulum system and forced tilting system

	Pendulum system	Forced tilting system
Tilting force	Centrifugal force and auxiliary pneumatic power	Hydraulic power or pneumatic power
Tilting center height	Over carbody gravity center (Necessary)	Under carbody gravity center (Allowable)

solving the above problem, a forced tilting control system is required. This system enables the carbody gravity center to shift toward the inside of a curve.

Accordingly, in cooperation with East Japan Railway Company (JR-EAST), we have developed a tilting control system using a long-stroke air spring as a type of forced tilting control system$^{2)\sim5)}$. This system aims at increasing curving velocity up to 120 km/h, which is about a 20 km/h excess over a pendulum train's curving velocity, on 400 m radius curves. Using the system, the target speed was successfully achieved on a running test.

This paper deals first with the curving performance of a tilting train. The tilting system developed and the running test results are then described.

2. Curving Performance of Tilting Train

2.1 Ride Quality Affected by Centrifugal Acceleration

Lateral ride quality on curves is affected by stationary lateral acceleration (α_s) as shown in **Fig. 1**. Here, α_s is obtained by subtracting the equivalent acceleration to cant angle and carbody tilting angle from centrifugal acceleration. **Figure 2** shows the relation between α_s and curving velocity on a 400 m radius curve. Since α_s should be less than 0.78 m/s^2 for good ride quality, the tilting angle required is 7 degrees at a 120 km/h curving velocity.

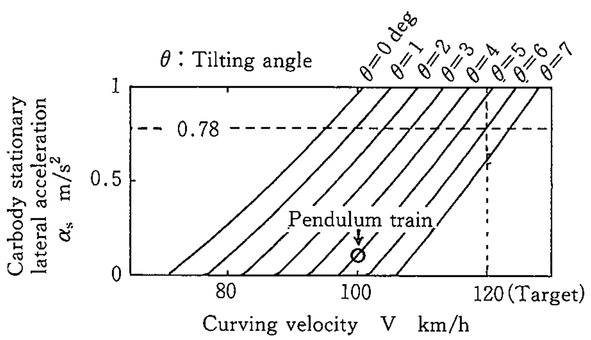


Fig. 2 Calculated carbody stationary lateral acceleration on a 400m radius curve

2.2 Running Safety on Curves

Running safety is judged by wheel load and lateral thrust acting on the contact point between wheel and rail. Wheel load is especially affected by the tilting mechanism. **Figure 1** also shows wheel load. The wheel load changes when the centrifugal acceleration is loaded or the carbody gravity center is laterally shifted by tilting.

The ratio of changing wheel load (Δp) to static wheel load (p_0) is called wheel unload ratio ($\Delta p/p_0$). $\Delta p/p_0$ should be less than 0.6 stationary and 0.8 dynamically because of the running safety margin against overturning. **Figure 3** shows a example of stationary $\Delta p/p_0$ affected by the tilting center height on a 400 m radius curve. Since the tilting center height of most pendulum trains is 2.275 m, $\Delta p/p_0$ will exceed 0.6 if the velocity increases toward 120 km/h with the same tilting center height. Thus the tilting center height must be lowered below about 0.9 m to achieve equivalent running safety to pendulum trains.

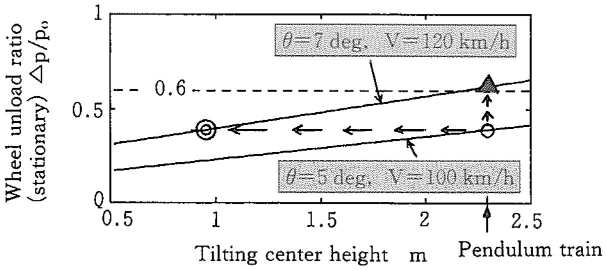


Fig. 3 A calculated example of wheel unload ratio affected by tilting center height

3. Tilting System

3.1 Tilting System Using Air Springs

A tilting system using air springs was selected as the forced tilting system on account of the following advantages.

(1) Tilting center height can be low — less than 0.9 m above the rail.

(2) Bogies can be relatively light and simple.

A tilting control system using air springs, with tilting angle limited to about 2 degrees, has already been tried out on some lines during 1993-1994[6)~8)]. This system consumes compressed air whenever the carbody tilts. Yet, considering consecutive curve negotiation with a 7 degree tilting angle instead of 2 degrees, large air consumption causes a supply shortage of compressed air for the air springs. Consequently an non air-consuming tilting mechanism has been developed.

3.2 Tilting Mechanism

Figure 4 schematically shows the tilting mechanism developed. This mechanism mainly consists of two long-stroke air springs mounted on a bogie and a double-acting air cylinder driven by an oil-hydraulic actuator.

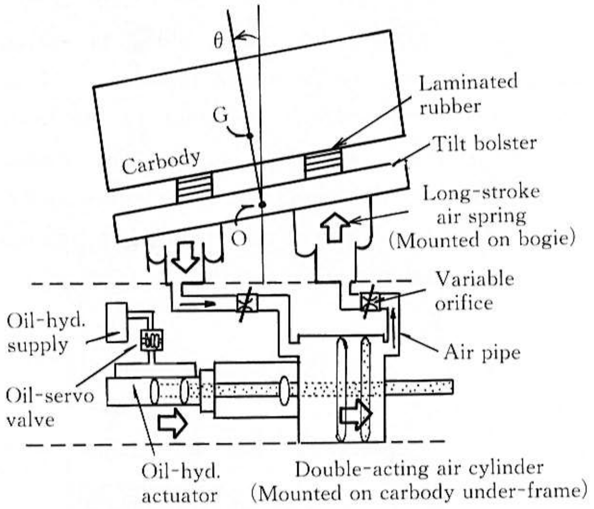


Fig. 4 Tilting mechanism schematic

Photo 1 shows a long-stroke air spring. This air spring can vertically expand or compress up to ± 140 mm for a 7 degree tilting angle.

Photo 2 shows the tilting-drive unit consisting of a double-acting air cylinder and an oil-hydraulic actuator. The unit is mounted on a carbody underframe. The double-acting air cylinder enables a carbody to tilt without air consumption.

Photo 1 Long-stroke air spring mounted on a bogie

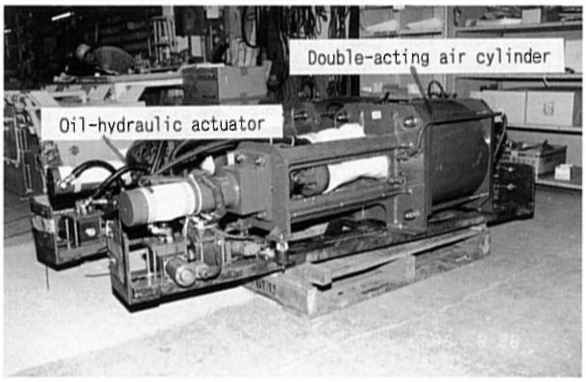


Photo 2 Tilting-drive unit

3.3 Bogie

Photo 1 also shows a bogie equipped with the tilting device. This bogie's performance provides excellent running stability, high ride quality, and light weight.

4. Control Method

4.1 Tilting Control

The tilting control adopts a program control method in order to compensate for tilting or restoring response lag at the beginning or end of curves. **Figure 5** shows the tilting control method. The control cycle starts with measuring running velocity using a tacho-generator. Integrating the running velocity then obtains the calculated running position. Moreover, the calculated running position is occasionally corrected at correcting points by the method described in the next chapter.

Next, using the corrected running position and previously memorized curve data, a target tilting pattern for the next curve can be estimated in advance. This pattern is generated earlier than the curve entry point for response lag compensation.

Finally, a control signal is output to the servo valves by a control adopting the deviation between the target tilting angle of the pattern and the measured tilting angle.

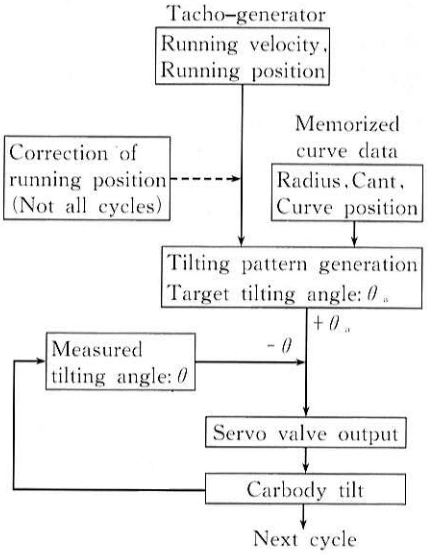


Fig. 5 Tilting control flowchart

4.2 Correcting Method of Running Position

The calculated running position must be corrected because errors are gradually accumulated. **Figure 6** shows an idea of the correcting method. A calculated curvature is caused by the calculated running position and by the curve data. When the calculated curvature is locationally checked against the measured curvature, it is locationally shifted toward the measured curvature. Therefore the calculated running position is corrected in terms of the distance shifted.

Since this method does not require wayside devices such as ground coils, it can apply to all railway systems.

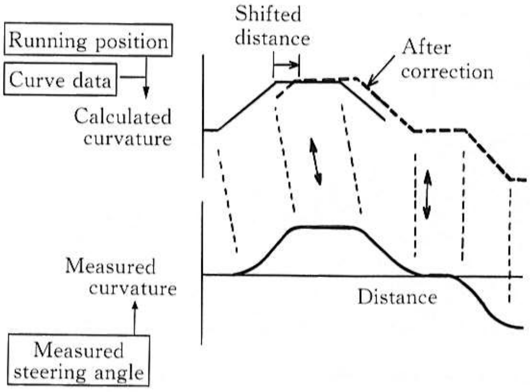


Fig. 6 Idea of correcting method

4.3 Fail-Safe

Mechanical leveling valves (LV), which keep the air spring height constant, are designed with fail-safe mechanisms. In case of control system failure, The LV restores the tilting carbody to upright. At the same time, failure information is displayed in the driving cab so that a driver can brake the train to a non-tilting restricted curving velocity.

5. Running Test

5.1 Experimental Car

Photo 3 shows the narrow gauge experimental electric train "TRY-Z". TRY-Z has been developed by JR-EAST in order to develop new railway technology. The tilting control system was installed in the middle car of TRY-Z. **Photo 4** shows a 7 degree tilt on a control test.

Photo 3 JR-EAST's experimental electric train 'TRY-Z'

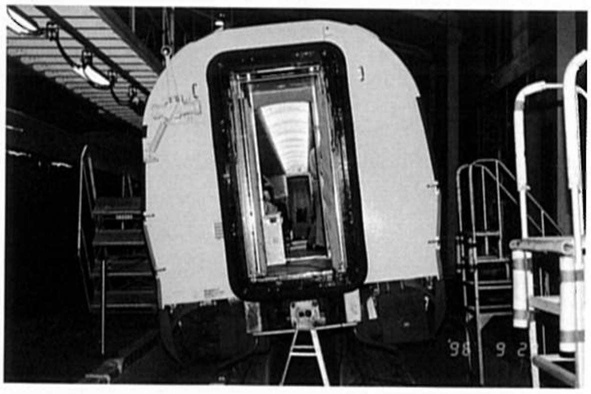


Photo 4 7 degrees tilting carbody on a control test

5.2 Test Section

Running tests were held on the Chuo main line in 1995 and 1996. The test section is 31 km long and has at least 56 curves whose radiuses are mostly 400 m.

Table 2 shows restricted curving velocity on a 400 m radius curve in the test section.The target velocity is 20 km/h higher than the velocity of the pendulum train.

Table 2 Restricted curving velocity on a 400m radius curve

Car type	Velocity km/h
TRY-Z (Target)	120
Controlled pendulum limited express	100
Non-tilting limited express	90
Ordinary car (Basic)	75

5.3 Test Results

5.3.1 Control Performance

Figure 7 shows control performance during consecutive curves. Since the calculated curvature was fitted to the measured curvature by correction, the measured tilting angle locationally fitted the measured curvature.

Figure 8 shows the comparison between target tilting angle and measured tilting angle on a 400 m radius curve. The measured tilting angle fitted well with the target tilting angle. Therefore control performance was successful.

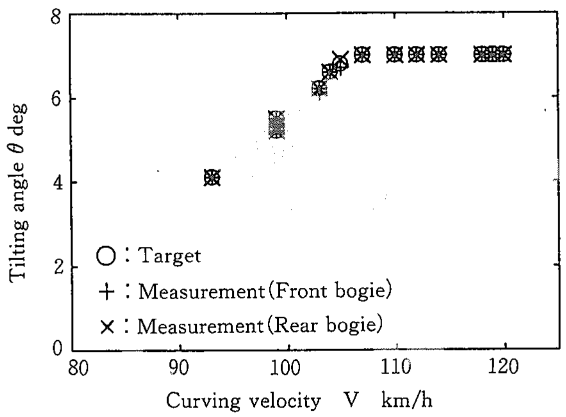


Fig. 8 Measured tilting angle compered with target tilting angle

5.3.2 Running Safety on Wheel Unload

Figure 9 shows the wheel unload ratios on a 400 m radius curve. The stationary wheel unload ratio was under 0.6 and was almost equal to the calculation. The dynamic wheel unload ratio was also under 0.8. Therefore running safety in terms of wheel unload was adequately satisfied.

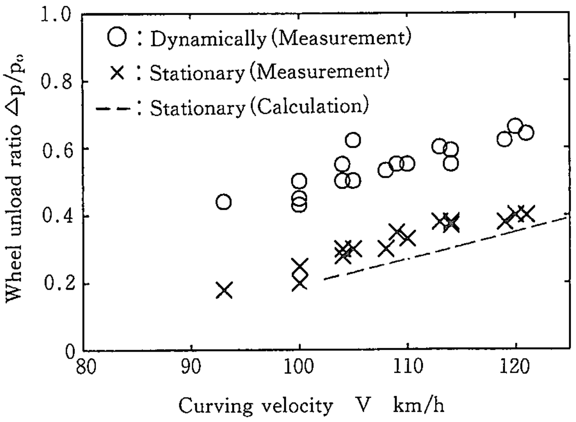


Fig. 9 Wheel unload ratio on a 400m radius curve

5.3.3 Ride Quality for Centrifugal Acceleration

Figure 10 shows the stationary lateral acceleration on the carbody on a 400 m radius curve. The stationary lateral acceleration was under 0.78 m/s^2 and was almost equal to the calculation. Therefore the ride quality with regard to centrifugal acceleration was good.

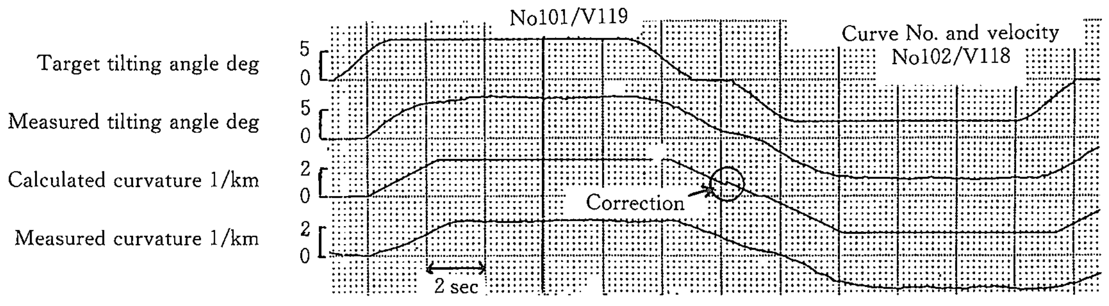


Fig. 7 Control performance during the consecutive curves

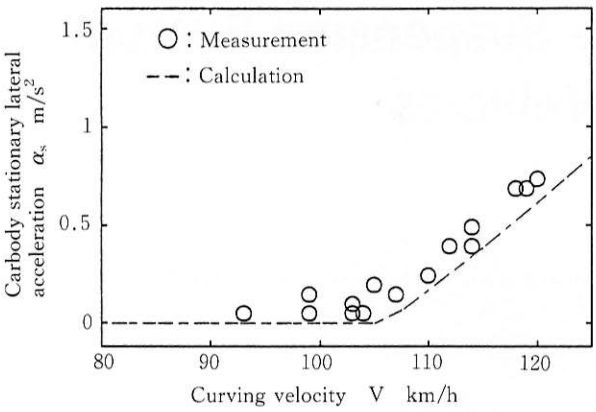


Fig. 10 Carbody stationary lateral acceleration on a 400m radius curve

6. Conclusion

In cooperation with JR-EAST, we have developed a tilting control system in order to raise speeds to a 120 km/h curving velocity on 400 m radius curves. From the running test results, the tilting control was successful. Adequate running safety and good riding performance were also verified, with the target curving velocity being achieved. Accordingly, we are confident that this tilting control system is very appropriate for achieving higher speeds on sections with many consecutive curves.

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