Tilt Control Mechanism with Rotary Actuator and Anti-roll Bar

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This paper describes the development of a bogie equipped with a new type of tilt mechanism capable of providing a tilt of up to 5 degrees which is the same maximum tilt angle as the conventional bolster-type tilt mechanism, though with simpler structure. The tilt mechanism proposed provides the tilting forces to the carbody by adding torsional torque to the torsion bar on the anti-rolling device. The rotary actuator, which is inserted between the torsion bar and the arm in series, generates the torsional torque. The arms and the vertical links transmit the torque to the carbody. A bench test for simulating running on a curve and carbody tilting was conducted. The results demonstrate that it is possible to tilt the carbody with high responsiveness according to the target tilt pattern up to 5 degrees.

Keywords: carbody tilting, bogie, anti-rolling device, maintenance-free, ride comfort, motion sickness

1. Introduction

On a bogie (pendulum bogie) of the “controlled natural pendulum” type which is a carbody tilting type commonly used in Japan, a pendulum beam for tilting the vehicle body is mounted on the bogie frame via bearings such as a roller device. This means that pendulum bogies have a structure that is more complicated than ordinary bogies, resulting in more time and cost required for maintenance.

A simpler type of tilting carbody which uses air springs is used for Shinkansen trains. However, because of its structure, the maximum tilt angle is limited to approximately 2°, which is smaller than that of the pendulum (5° to 6°), making it difficult to significantly reduce the excess centrifugal acceleration on a meter-gauged railway line with consecutive sharp curves. Furthermore, this type of tilting carbody structure consumes a significant amount of compressed air to extend the air springs.

This paper therefore proposes a new carbody tilting mechanism that has a simpler structure than pendulum bogies but is capable of producing the equivalent maximum tilt angle of pendulum bogies. In developing this mechanism, steps were also taken to try to reduce motion sickness, which must be taken into consideration for ride comfort on tilting carbody vehicles. The goal was to implement the control performance that can follow the RTRI-developed “JTM pattern [1],” which is a carbody tilt pattern (consisting of target values of continuous carbody tilt angles) that reduces low-frequency lateral motion: the primary cause of motion sickness.

The configuration of the carbody tilt mechanism, the specification study by simulation, and the results of the fixed tilting test with the prototype mechanism and bogie are described below.

2. Anti-rolling device type carbody tilt mechanism

2.1 Configuration of the tilt mechanism

Figure 1 shows the proposed carbody tilt mechanism. It has a structure that applies a forced torque to the torsion bar spring (1) of an ordinary anti-rolling device so that the tilting force can be applied to a carbody. A motorized rotary actuator (2) is used to generate the torque, for responsiveness and compactness. The tilting force is transmitted to the carbody via the arms (3) and the vertical links (4). Since the maximum tilt angle is as large as 5°, if the air springs (5) are disposed at an ordinary lateral distance of approximately 1.6 to 2.0 m, a large vertical stroke must be allowed. It was therefore decided to make the lateral distance of the air spring narrower than in the ordinary disposition. This mechanism is a so-called “carbody tilting above secondary suspension” without any pendulum beam; therefore, in a curve with cant deficiency, the lateral...
movement of the carbody against the bogie would be large, creating the concern that ride comfort could be reduced due to the lateral motion and contact with lateral bump stops. To solve this, a centering actuator [2] (6) was added to suppress lateral movement of the carbody. In general, tilt mechanisms with high stiffness tend to transmit bogie vibrations to the carbody; however, it provides better insulation against vertical vibration because of the linked structure that allows vertical relative-displacement between the bogie and carbody.

2.2 Forces acting on carbody during carbody tilting

Figure 2 shows the main forces acting on the carbody when it tilts while traveling through a curve. For simplicity, the figure shows each force as a horizontal or vertical force on the rail surface. The forces resisting the centrifugal force acting on the center of gravity of the carbody are the gravity horizontal direction component force on upper surface of bogie frame, the lateral force of air springs, and the centering actuator force. Since the center of gravity of the carbody is usually at a higher position than the points of action of the air spring lateral force and the centering actuator force, an outward tilting moment acts to cause the carbody to tilt out of the curve. In contrast, the air spring vertical force and the vertical link force caused by the torsional stiffness of the torsion bar generate the counter moment. At this time, the rotary actuator generates torque to increase the vertical link force, thereby causing the inward tilting moment (necessary for carbody tilting) to act and enabling carbody tilting. Meanwhile, since the air spring vertical force moment usually acts in the direction that allows the carbody to be kept horizontally, it acts as a resistance force to carbody tilting.

3. Study on Specifications and verification by simulation

3.1 Required specifications for the components

To study the required specifications for the components, the following steps were taken: First, one vehicle model equipped with the above tilt mechanism was constructed using the multibody dynamics simulation software SIMPACK. Second, the vehicle was run at 85 km/h (curved passing speed of a controlled natural pendulum vehicle) on a curve with a radius of 300 m and a cant of 105 mm (typical of a sharp curve on a meter-gauge railway line). The carbody tilt angle was then verified. The conditions in which a tilt angle of 5° was achieved were sought by sequentially varying three parameters: the required torque for the rotary actuator, the torsion stiffness of the torsion bar to transmit the tilting force to the carbody, and the lateral distance of the air spring that provides resistance to the tilt. The air spring used was a simple linear one. As a result, the mechanism achieved a tilt angle of 5° and succeeded in following the JTM pattern when the maximum torque of the rotary actuator was 3 kNm, the torsional stiffness of the torsion bar was 40 kNm/rad, and the air spring lateral distance was 1 m. Figure 3 shows a summary of the calculation results of the tilt angle and the actuator generation torque in the front traveling bogie.

The items used for verification obtained from the results of the analysis are shown below.

3.2 Effect of track twist on tilt control

While traveling on the transition curve, it was observed that the rotary actuators of the front and rear bogies exerted forces in opposite directions to each other due to the effect of track twisting (flatness), causing them to be in tension. Such a phenomenon not only requires a large tilting force but may also affect the vehicle running safety. This phenomenon occurred when the tilt patterns of the front and rear bogies of the conventional carbody tilt vehicles were identical, it may not have appeared because neither the maximum generating force nor the responsiveness of the tilting actuator were very high.

To overcome this problem, a proposal was made to improve followability to the track twist by advancing the tilt pattern of the rear traveling bogie, by the traveling time for the running distance between the bogie centers, with respect to the front traveling bogie [3]. Figure 4 shows the comparison of the calculation results of the leading axle outside rail wheel load for when the tilt pattern was identical for both the front and rear bogies and when the components...
mand to the rear bogie was advanced. This approach suppressed both the increase in wheel load on the transition curve near the entrance and the decrease in wheel load on the transition curve near the exit.

3.3 Effect of lateral deviation of carbody center-of-gravity

It was found that when the carbody center-of-gravity deviated from the center of the carbody to the lateral direction, a large actuator force was required to retain the carbody roll moment due to this deviation. Consequently, a load would have to be continuously applied to the rotary actuator even when running in straight sections, which is undesirable. One of possible solutions for this is to improve the roll supporting stiffness by the air springs disposed on the left and right (hereinafter “air springs roll stiffness”) as well as the tilt mechanism.

3.4 Effect of improvements on motion sickness

The followability of the carbody tilt angle was effective for matching the JTM pattern. The impact of the improvement on motion sickness was verified using the motion sickness dose value [4] (MSDVy). Motion sickness is generally felt as a result of the cumulative action of vibrations on the human body, making it desirable to suppress the MSDVy as much as possible. Figure 5 shows a continuous waveform of short-term MSDVy obtained by running on a continuous curve, assuming an actual commercial line (each MSDVy was calculated from the lateral acceleration for a total of 20 seconds before and after). Compared to the model simulating the conventional controlled pendulum vehicle, this mechanism succeeded to reduce the short-term MSDVy to 1/3 to 1/2 and suppress it to approximately 1 m/s$^{1.5}$. This is equivalent to the value obtained when a conventional limited express vehicle runs in a straight line, and suggests that this mechanism should reduce motion sickness.

4. Prototyping of Tilt Mechanism

The component parts were selected on the basis of specifications formulated through simulation and those of the test equipment used for the experiment, and a prototype was made of the tilting mechanism.

4.1 Rotary actuator and torsion bar

After researching the market for power-operated rotary actuators, the Harmonic Drive Systems SHA65 (Fig. 6) was selected, as it was the most compact model with the largest torque. It contains a motor and a drive gearing speed reducer (reduction gear ratio 1:161) and has a maximum torque of 3.4 kNm. It also has a braking system that fixes the input and output shafts when not energized. In addition, a prototype torsion bar was made to which the rotary actuator could be attached with a torsional stiffness of 40 kNm/rad.

4.2 Centering actuator

A centering actuator was used with compressed air as the driving source [2]. This cylinder does not require a controller or sensor because it contains a mechanical valve mechanism in the piston rod to generate a reaction force (up to approximately 10 kN) depending on the displacement. It has a dead zone near the neutral position in order to suppress unnecessary reaction forces when a vehicle is running in a straight line and has the characteristic that in the case of displacement of the carbody when it is running through a curve, a large reaction force is generated.

4.3 Air spring

Since the air spring lateral distance was set to 1 m, it was necessary to avoid interference with the center pin and thus a ready-made product with a relatively small outer diameter (effective diameter 460 mm) was selected.

5. Tilting Test with Stationary Test Equipment

5.1 Configuration of test equipment

The tilt mechanism was temporarily installed on the vibration load test equipment that can simulate various modes of vibration on the vehicle, and conducted the stationary tilt-
ing test. Figure 7 shows the configuration of the test equipment. The actuator (7) simulated the excess centrifugal force acting on the carbody. Figure 8 shows the installation status of the tilt mechanism. We temporarily installed the tilt mechanism on the bogie to limit the space taken by the test equipment. The carbody mass was 12.5 tons (half a carbody).

5.2 Results

5.2.1 Followability to the tilt pattern

A simulation was performed of running through a continuous curved section. Figure 9 shows time-series response waveforms of the carbody tilt angles and the tilting forces (i.e., longitudinal forces acting on the vertical link measured by a load cell). The tilting motion was smooth in all of the various conditions that were set for the test. As in the simulation, good followability was obtained in relation to the JTM pattern.

5.2.2 Communication between the left and right air springs

Based on the results of the simulation, it was decided to give the air spring system similar roll supporting stiffness in consideration of the left-right imbalance of the carbody mass and the fail-safe property. However, it is considered that when the vehicle tilts, the air spring roll stiffness becomes a resistance and requires a larger tilting force. To verify this disadvantage solenoid valves were provided for communication between the left and right air springs (auxiliary air reservoir), and compared the tilting performance when the air spring roll stiffness was lowered.

As a result of the test, no effect was found on the carbody tilt angle as shown by the blue and red curves in Fig. 9. On the other hand, a reduction in the tilting force of approximately 30% on average was observed in the circular wave when communication was made between the air springs. However, in the transition curve which includes the tilt being in the transient state, the reduction of the tilting force was only approximately 10% at maximum, and at a high tilting speed, a larger tilting force was occasionally required than in the non-communication case. It is presumed that the flow rate performance of each solenoid valve used for communication was insufficient and it took time to balance the inner pressure between the left and right air springs.

5.2.3 Effect of lateral deviation of carbody center-of-gravity

To verify the effect of the lateral deviation of the carbody center-of-gravity, the position of the deadweight loaded on the carbody was adjusted and another a tilting test was conducted when the center of gravity had been shifted 25 mm. In the conditions where the left and right air springs did not communicate, no significant difference was found in the carbody tilt angle. On the other hand, in the condition where the left and right air springs did not communicate, no significant difference was found in the carbody tilt angle as shown by the blue and red curves in Fig. 9. On the other hand, a reduction in the tilting force of approximately 30% on average was observed in the circular wave when communication was made between the air springs. However, in the transition curve which includes the tilt being in the transient state, the reduction of the tilting force was only approximately 10% at maximum, and at a high tilting speed, a larger tilting force was occasionally required than in the non-communication case. It is presumed that the flow rate performance of each solenoid valve used for communication was insufficient and it took time to balance the inner pressure between the left and right air springs.

5.2.4 Control failure test

Vehicle behavior was verified when the control power was lost during tilt control. When the torque of the rotary actuator was released (with the built-in brake released as well) during tilt control, the carbody lost the roll supporting stiffness and tilted outward due to centrifugal force (reverse tilt state). This shows that in order to make the
mechanism fail-safe, it is necessary to quickly secure the roll supporting stiffness of the carbody when the torque and brake force of the actuator are lost.

6. For Practical Use of the Proposed Carbody Tilt Mechanism

6.1 Study on the state switching function of the carbody support device

6.1.1 System configuration

Implementing the proposed mechanism requires state switching between the co-existing carbody support devices. Figure 10 shows the proposed system configuration of the carbody support device corresponding to the proposed mechanism.

A normally open solenoid valve (hereinafter, “LV solenoid valve”) that disables the height adjustment function of a leveling valve (hereinafter, “LV”) for an ordinary air spring vehicle between the LV and each air spring. A pipe line was then added that connected the left and right air springs (or auxiliary air reservoir) and a communication solenoid valve (hereinafter, this is called “communication solenoid valve”) between them. Table 1 lists the actions of the solenoid valves and other components on tilt control, including the other necessary switching elements.

6.1.2 Action on tilt control failure

If a failure occurs in the carbody tilt control system or its peripheral system, the tilt control must be stopped to ensure safety. Table 2 lists the actions of the solenoid valves and the behavior of the carbody responding to the control power being lost. These actions prevent the carbody from losing the roll supporting stiffness against the bogie, and secure the fail-safe property. The carbody could, however, remain fixed in a tilted state if the power is lost during tilting, for example, in a circular curve. As one of the possible measures against this, it was thought that setting the brake holding power for the time of non-energization of the rotary actuator could recover the carbody position horizontally so that the air spring vertical force by the LV height adjustment function could overcome it.

6.2 Prototyping the bogie

A study was made of the equipment components of the bogie and its layout to mount the anti-rolling device type carbody tilt mechanism using an ordinary meter-gauged bolsterless bogie as the base. A prototype of the bogie was made. Figure 11 shows the prototype bogie, which was manufactured with a structure that had a tilt mechanism on the carbody, taking into account the running vibration applied to the rotary actuator and the component layout of the bogie.

To implement the 1 m air spring lateral distance mentioned above, the structure supported the air springs with a connection beam connecting the cross beams, although the air springs of a typical bolsterless bogie were disposed on the side beam or outside.

7. Tilting Test with Prototype Bogie

A stationary tilting test was conducted to evaluate the carbody tilting performance of the prototype bogie.

7.1 Test method

As shown in Fig. 12, a load frame (14.7 tons in the 1/2 vehicle condition) equivalent to a carbody was mounted on

### Table 2 Actions of the solenoid valves and other components on tilt control failure

| Component name                        | Operating state | Purpose                                                                 |
|---------------------------------------|-----------------|-------------------------------------------------------------------------|
| LV solenoid valve                     | Closed          | To disable the vehicle height adjustment function by LV so that the tilting action will not be disturbed. |
| Communication solenoid valve          | Open            | To reduce the roll stiffness of the air spring system, thereby reducing the resistance during tilting action. |
| Tilt actuator brake                   | Brake released  | To release the restraint of the tilt actuator to make it controllable.   |
| Centering solenoid valve              | Open            | To enable centering control.                                            |

### Table 1 Actions of the solenoid valves and other components on tilt control

| Component name                        | Operating state | Purpose                                                                 |
|---------------------------------------|-----------------|-------------------------------------------------------------------------|
| LV solenoid valve                     | Closed          | To disable the vehicle height adjustment function by LV and the carbody is controlled horizontally. |
| Communication solenoid valve          | Closed          | The left and right air springs are made independent, and the roll stiffness of the air spring system is secured. |
| Tilt actuator brake                   | Brake released  | The roll stiffness is secured by the torsion bar.                        |
| Centering solenoid valve              | Closed          | Centering control is released.                                          |

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Fig. 10 Proposed system configuration of the carbody support device

Fig. 11 Prototype bogie with anti-rolling carbody tilting device
the prototype bogie. The JTM pattern simulating actual running was controlled as the target angle with various curve radii and set cant values. The excess centrifugal force generated in curves was simulated by pulling the assumed center-of-gravity height of the carbody laterally via a wire rope.

7.2 Results

Figure 13 shows the carbody tilt angles and actuator current values that resulted from the With- and Without-Communication conditions. Since the communication solenoid valve used in Section 5.2.2 had an insufficient opening area, a ball valve with an opening area of about 66 mm² was used for this test.

The carbody tilt angle followed the tilt pattern with almost no delay with or without communication. The maximum tilt angle in the circular curve was larger however with communication than without. The current in the circular curve exceeded the continuous rating when without communication, whereas it was reduced by 35% and was around the continuous rating with communication. The maximum current was also reduced by 33% in the transition curve. The above strongly suggests that air spring communication is an effective means for reducing the tilting force.

In tests where the carbody center-of-gravity was displaced 62 mm to the outside of the curve, the current in the circular curve exceeded the continuous rating. Consequently, this reveals that necessary measures include the following: (1) design a carbody that suppresses lateral deviation of the carbody center-of-gravity as much as possible, (2) use an actuator with a margin of output in consideration of

8. Conclusion

This paper proposes a mechanism which uses an anti-rolling device as a new carbody tilting mechanism that has a simple structure compared to a pendulum bogie and is still able to achieve the maximum tilt angle equivalent to that of a pendulum bogie. The following findings were obtained after studying the configuration of the tilt mechanism and testing the stationary tilting test using a prototype mechanism and bogie:

- A tilt equivalent to that of a pendulum bogie (5°) was achieved by setting the maximum torque of the rotary actuator to 3 kNm or more, setting the torsional stiffness of the torsion bar to approximately 40 kNm/ rad, and setting the air spring lateral distance to approximately 1 m.
- The above specification enables the mechanism to achieve the followability to the JTM pattern, which requires high responsiveness; this mechanism should therefore reduce motion sickness.
- For this mechanism to be used for tilt control, track twist (flatness) in transition curves, needs to be taken into account. To this end, advancing the carbody tilt pattern input to the rear traveling bogie by traveling time for the running distance between bogie centers against the front traveling bogie, was found to be effective.
- Communication between the left and right air springs is effective in reducing the tilting force. However, the solenoid valve selected for this purpose needs to have a sufficient flow rate performance.
- The lateral deviation of the carbody center-of-gravity requires a larger tilting force. The measures required for this include the following: (1) design a carbody that suppresses lateral deviation of the carbody center-of-gravity as much as possible, (2) use an actuator with a margin of output in consideration of
lateral deviation, and (3) in straight sections, provide an air spring system with carbody roll supporting stiffness, through communication between the left and right air springs.

- Even if the carbody tilt control fails due to any abnormality, the tilt mechanism must not lose its stiffness. However, since the carbody needs to be returned to a horizontal position, it is necessary to have a fail-safe mechanism that uses the automatic height adjustment function of the air spring, by using an LV, for example.

Future work aims to focus on component development and fail-safe system design, in order to conduct further studies for the practical application of this carbody tilting mechanism.

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