Improvement of the Lateral Ride Comfort on Railway Vehicles by Application of Pneumatic Actuators for Centering

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To improve the lateral ride comfort of vehicles, trials were conducted applying a pneumatic actuator with a displacement dependent control valve. The valve installed on the actuator rod controls the force generated by the actuator depending on the relative displacement between the vehicle body and the bogie. This control makes it possible to keep the vehicle body around the neutral position. The actuator was installed on a test vehicle. The results of the running tests show that the actuator has the ability to decrease impacts caused by collisions against the lateral bump stop. Reducing the impact leads to lower lateral vibrational acceleration of the vehicle, and thus, better ride comfort. The actuator can operate independently using only a compressed air supply, and therefore there is no need to equip the actuator with electrical sensors and control devices.

Keywords: lateral bump stop contact, ride comfort, neutral position control, pneumatic actuator

1. Introduction

The advantage of tilting trains is that they improve the running speed through curves by reducing the steady lateral acceleration experienced by the passengers. A few types of tilting system are used in the world [1, 2]. Among them, two typical types are used in Japan. One is a passive pendulum type which has a swaying bolster with a circular arc guide, and another is a type of tilting which is directly controlled by applying active control to the secondary roll suspension. Controlling the length of secondary suspensions corresponds to the latter approach. This type has the advantage of making the bogie structure simpler, because it is not necessary to equip it with a swaying bolster. However, this design has a weak point, which is that the lateral displacement of the vehicle body relative to the bogie while running on curves increases with speed. It leads to lateral bump stop contact. The impact between vehicles body and bogies is one of the causes of poor ride comfort [3]. The role of the lateral bump stop is to prevent excessive lateral movement of the vehicle body, due to excessive input associated with centrifugal force and track irregularities, to ensure vehicles stay within their clearance gauge. For this reason, it is impossible to spread the lateral gap between the vehicle body and the bogie around the bump stop. To suppress lateral displacement of the vehicle and to maintain the vehicle body around the neutral position while tilting, the ETR450 in Italy has actuators for centering [4, 5]. The size of the actuator is large and it is necessary to arrange control valves and complex pneumatic piping on the vehicle body. As a result, adopting the same actuator for bogies on meter gauge vehicles in Japan would be difficult, without major modification.

Pneumatic Servo Controls, Ltd. and Sumitomo Metal Industries, Ltd. (now NIPPON STEEL & SUMITOMO METAL CORPORATION) in Japan, developed a small pneumatic actuator which has a mechanical feedback system to maintain the vehicle body around the neutral position without control units and sensing devices [6]. The Railway Technical Research Institute and the Shikoku Railway Company presented the specifications of the pneumatic actuator to be applied to the bogies for meter gauge vehicles and verified its performance in validation tests. This paper describes the effectiveness of improving ride comfort by applying the pneumatic actuator to tilting trains of the type controlling the length of secondary suspension.

2. Lateral bump stop contact and the actuator for suppressing the bump stop contact

2.1 Lateral bump stop contact

Railway vehicles have a lateral bump stop. The role of the lateral bump stop is to prevent excessive lateral movement of the vehicle body due to excessive input associated with the centrifugal force and track irregularities, ensuring vehicles stay within their clearance gauge. Bump stop rubbers are normally installed on bogies for buffering the impact of the vehicle body. There is a gap of 10 to 30 mm between the bump stop rubber and the vehicle body in the neutral position (Fig. 1). The bump stop rubber is not in contact with the vehicle body while running on straight track. When running through switches or through curves at high speed however, the bump stop rubber is in contact with the vehicle body (Fig. 2). This contact is referred to as hard lateral bump stop contact. This is due to the hard contact between the lateral bump stop between vehicle body and bogie, at the relatively high cant deficiency. Vibrations which cause ride comfort to deteriorate arise from this action. Moreover, the bump stop rubber works as a coupling
element transmitting vibrations from track irregularities to the vehicle body if the contact between the bump stop rubber and the vehicle body is maintained while running through long curves, which also has a negative impact on ride comfort.

The lateral bump stop prevents excessive lateral movement of the vehicle body and guarantees that the vehicle remains within the clearance gauge. Considering this aspect, there is a limit for the maximum gap which can be allowed between the bump stop rubber and the vehicle body. Consequently, widening the lateral gap between the vehicle body and the bump stop rubber would be impractical. Therefore, to avoid worsening ride comfort, contact between the vehicle body and the lateral bump stop should be prevented and the vehicle body should be kept around the neutral position. Ordinal lateral bump stop rubber has a void inside; for this reason, it can be assumed to have two rigidity characteristics. Firstly, a low rigidity region appearing until the void is pressed flat, the other is a high rigidity region appearing after the void has been pressed completely flat (Fig. 3).

### 2.2 Pneumatic actuator for centering

The pneumatic actuator for centering suppresses relative lateral displacement between the vehicle body and the bogie while the railway vehicle is running through curved sections. It generates a reaction force depending on the relative lateral displacement. There is a lateral damper which connects the vehicle body to the bogie to attenuate lateral movement of the vehicle body. The centering actuator is installed parallel to the lateral damper. The response sensitivity of the actuator was set to low, around the neutral position to avoid generate a force while running on straight track. Where possible, the actuator should not respond to high frequency vibration, to avoid transmitting bogie vibrations to the vehicle body. There are various possible sources for generating force such as compressed air, hydraulic oil, electric motor and so on. Compressed air is used in many railway vehicle devices, and is characterized by its ability to isolate high frequency vibrations from the bogie. Accordingly, compressed air was selected as the actuator power source for centering. Furthermore, the actuator was not equipped with an electrical control system to reduce its size and cost.

### 3. Prototype of the pneumatic actuator for centering

#### 3.1 Structure of the pneumatic actuator for centering

The prototype pneumatic actuator for centering (Fig. 4) generated reactive forces depending on the displacement of the piston. Figure 5 shows the mechanism of the actuator. A constant flow of compressed air was supplied to the actuator cylinder through the orifice installed on the air supply port. The generated force was controlled by opening / closing the atmospheric open valve (exhaust ports) depending on the displacement of the piston. The generated force was suppressed around the neutral position by connecting the head side with the rod side of the cylinder with the communication pipe. The air was also simultaneously evacuated through the orifice of the atmospheric open valve (Fig. 5(B)). When the rod of the actuator was displaced and shortened by the external force, the atmospheric open valve of the head side of the cylinder was closed and at the same time the compressed air remained in the rod side of the actuator.
time, the valve of the rod side of the cylinder was opened wide to create a large pressure difference in each cylinder in order to increase the reaction force (Fig. 5(A)). On the other hand, when the rod of the actuator was displaced and lengthened by the external force, the atmospheric open valve was opened on another side to increase the reaction force in the other direction (Fig. 5(C)). These atmospheric open valves and the port of the communication pipe were installed on the rod of the piston to minimize the size of the actuator.

3.2 Generated force characteristic of the actuator for centering

Figure 6 shows the generated force of the actuator for centering when the supplied air pressure was set to 800 kPa (gauge). The piston of the actuator was displaced towards the head and the rod. The forces are shown as the absolute values corresponding to the frequency of the external displacement. The generated force was between 1.7 and 2.5 kN when displacement equaled 5 mm and the frequency equaled 0.01 Hz, simulating the quasi-static movement of running in a curve section. However, when displacement exceeded 10 mm, the generated force varied between 4.8 to 5.9 kN to keep the vehicle body around the neutral position. Additionally, the generated force was suppressed at frequencies over 0.5 Hz, which has the advantage of reducing sensitivity to vehicle body vibration while running. Figure 7 shows the relationship between generated force and external displacement. The positive displacement corresponds to the displacement toward the head, while negative displacement corresponds to displacement toward the rod.

When displacement is over 3 mm where the external force frequency equals 0.01 Hz simulating quasi-static movement, the generated force exceeds 5 kN. Generated force is between 2 and 3 kN due to characteristics of compressed air however, when the frequency of the external force equals 2.0 Hz, simulating the vibrating motion of the...
vehicle body. The advantage of this, is that there is a slight response to the vibrating motion of the bogie and the vehicle body.

4. Running test for performance verification of the pneumatic actuator for centering

4.1 Condition of the running test

A running test was conducted with a four-car train. The pneumatic actuators for centering were installed on both the bogies of the leading vehicle. Figure 8 shows the actuator in position. The lateral relative displacement between the vehicle body and the bogie was measured with a displacement sensor which was installed on the actuator. The compressed air supply was stopped when the actuator was not in use, for comparison. The contact conditions between the lateral bump stop and the center pin of the vehicle body (hard lateral bump stop contact) was obtained by measuring the strain of the mounted member of the lateral bump stop (Fig. 9). Furthermore, to evaluate the ride comfort, lateral acceleration was measured by the accelerometer attached to the floor of the vehicle. The running tests for this paper were conducted in such a way as to ensure that the leading vehicle of the test train, equipped with the centering actuator, was always the head vehicle, and that leading vehicle test results were used.

4.2 Suppression of lateral vehicle displacement

Figure 10 shows the relative lateral displacement between the vehicle body and the bogie. The displacement corresponds to the displacement of the actuator for centering installed on the first bogie of the test vehicle. The vehicle ran at a velocity of 85 km/h on a curve of radius 300 m (20 km/h faster than the maximum velocity specified in the general rules, and a cant deficiency \( C_d \) equal to 97 mm). In this figure, “Control” means using the actuator and “Passive” means not using it. Displacement in the neutral position corresponds to 0 mm. The lateral displacement while running on a circular curve decreased from 30 to 20 mm when using the actuator (control). The generated force of the lateral bump stop rubber was relatively small when the center pin of the vehicle body came into contact with the lateral bump stop rubber in the low rigidity region and where the absolute displacement between the bogie and the vehicle body was 15 to 25 mm. This confirmed that the actuator for centering suppressed the vibration caused by the impact between the vehicle body and the bogie.

Figure 11 shows the relationship between the displacement of the actuator and the cant deficiency. Cant deficiency is the difference between the equilibrium cant and the set cant, that is calculated based on the unbalanced centrifugal acceleration \( \alpha_U \), track gauge \( G \) and gravitational acceleration \( g \) as follows.

\[
C_d = \alpha_U G / g \tag{1}
\]

Figure 11 compares results from data sets of when the actuator for centering was used and not used, when the difference in velocities in each data set were less than 5 km/h and the length of the circular curves were 51 m or more on the right hand curve. The red and white circles correspond to the results using the actuator and those not using it respectively. The lines connecting data obtained for a same curve were added for easier comparison of cases with and without the actuator.

Small displacements of 15 to 25 mm correspond to the contact of the lateral bump stop in the low rigidity region. The length of the connecting lines shows the degree of the effect of the actuator for centering. A longer line means that the actuator is effectively suppressing lateral displacement of the vehicle body. When the actuator was not used, the lateral bump stop came into contact with the center pin when the cant deficiency was 45 mm or more; moreover, the center pin came into contact with the bump stop in the high rigidity region of the bump stop rubber when the cant deficiency was 60 mm or more. The center pin did not come into contact with the bump stop when the cant deficiency was less than 75 mm and when the actua-
tor was being used. The actuator extended the maximum cant deficiency in the case of the center pin came into contact with the bump stop in the low rigidity region of the bump stop rubber to 100 mm when the actuator was being used from 60 mm of not being used. Results also showed that when the actuator was used, the cant deficiency range in which there was no contact, was also wider.

4.3 Reducing hard lateral bump stop contact

Figure 12 shows the stress on the mounted base of the lateral bump stop on the first bogie while running in a curved section. The result was measured on the same curve as that in Fig. 10. The data was filtered by 8 Hz low pass filter and trends were removed to focus on the low frequency region coming from the hard lateral bump stop contact. The stress measured was 5 to 10 MPa in the curved section when the actuator was not used, whereas it was 2.5 MPa or less with the actuator. The stress data also demonstrates the effectiveness of the actuator for mitigating hard lateral bump stop contact.

4.4 Improvement of ride comfort

Figure 13 shows the lateral acceleration measured on the floor of the vehicle right above the center of the first bogie. The data was measured on the same curve as that in

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**Fig. 11** Relationship between cant deficiency and displacement of pneumatic actuator for centering (1st and 2nd bogie of the test vehicle)

**Fig. 12** Stress on the back of the lateral bump stop caused by hard lateral bump stop contact (1st bogie of the test vehicle)

**Fig. 13** Lateral acceleration of vehicle (Above the 1st bogie of the test vehicle)
Fig. 10. The measured data was filtered by 15 Hz low pass filter. Double amplitude of the lateral acceleration using the actuator was 0.7 times larger than the results when no actuator was used. Impulsive lateral movement caused by the contact of the center pin with the lateral bump stop was suppressed.

Figure 14 shows that ride quality levels $L_T$ [7, 8] over short periods of time in the lateral direction calculated from data measured in sections with many curves of radius of around 300 m. The periods to evaluate ride quality levels over short periods of time were shorter than for ordinary ride quality level $L_T$. For this reason, ride quality levels $L_T$ over short periods of time are suitable for evaluating the ride quality of certain short sections. Figure 14 also shows curvatures. The ride quality level over short periods of time in Fig. 14 was calculated from the lateral acceleration measured on the floor of the vehicle right above the center of the first bogie. The ride quality level with the actuator was 2 to 4 dB lower than without. The effect on ride quality level using the actuator is most notable on long curves. It is well known that humans have the ability to feel a difference in ride quality level at about 3 dB [9]. Consequently, the improvement in ride comfort brought about by the actuator was large enough to sense. In some sections the ride quality level using the actuator appeared to be worse than without an actuator. This was because the running speeds in these sections with an actuator were higher than the speeds for which ride quality level was recorded without an actuator.

4.5 Guidelines for optimal design

By using the actuator, it is possible to have a wider cant deficiency range where the vehicle body comes into contact with the lateral bump stop rubber in the low rigidity region. This signifies that the actuator can extend the range of traveling conditions (traveling speed, radius of curve and cant deficiency) where ride quality can be maintained at a satisfactory level. It is possible to build the actuator cylinder to optimal size, by setting the generated force of the actuator cylinder to a level which will make it possible to avoid hard lateral bump stop contact in the high rigidity region of the lateral bump stop rubber, whilst considering restrictions due to the size of bogie parts. In order to reduce hard lateral bump stop contact where there is large cant deficiency, optimal design can be achieved by combining the method for improving the generated force of the actuator cylinder and improving rigidity of the secondary suspension in the lateral direction. Figure 11 also shows the equilibrium between centrifugal forces and reaction forces acting on the vehicle body when force is generated / not generated by the actuator cylinder. This can be useful for determining the mechanical characteristics of the actuator in consideration of the route, the running speed, the characteristics of the bump stop rubber and the gap between the vehicle body and the bogie.

5. Conclusions

Basic and running tests were carried out to validate the performance of the actuator for centering in ensuring ride quality of vehicle running at high speed in curved sections.

The actuator has the ability to keep the vehicle body around the neutral position to reduce hard lateral bump stop contact. The characteristics of the actuator were identified and test results obtained were as follows.

1. The actuator is a small pneumatic cylinder that generates force depending on the relative displacement between the vehicle body and the bogie. The valve for controlling the actuator is installed on the rod of the actuator. For this reason, the valve works independently by supplying compressed air. There is no need for equipping the actuator with electrical sensors and control devices.

2. The result of the running tests showed that the actuator has the ability to suppress lateral displacement of the vehicle body running in curved sections. This characteristic makes it possible to
mitigate hard lateral bump stop contact between the center pin of the vehicle body and the lateral bump stop rubber. The ride quality level ($L_T$) over short periods of time in the lateral direction when the actuator was used, was 2 to 4 dB smaller than when no actuator was used, in sections containing many small curves.

The actuator was installed on the 8600 express train series of the Shikoku Railway Company. The train is now operated on the main lines of Shikoku Island. Attempts are now being made to improve the performance of the actuator so that it can be applied to curves in more severe conditions.

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