Control Method of the Assist Steering System for Bolsterless Bogie Considering with Fail-safe Function

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Abstract

In order to decrease the lateral force generated in the railway vehicles in the curve sections, a simple steering system for the bolsterless bogie was developed [1]. The mono-link with the actuator function is used, and an appropriate steering force is added to supplement self-steering characteristic of the wheel-sets. The authors have designated this system as an “assist steering system”. In this paper, we report the result of fundamental running test in the test line and bench tests. As a result, it was apparent that the average lateral force in the circular curve section decreased by the assist steering control. In addition, considering fail-safe function, tandem cylinder actuator that can prevent reverse-steering mode and effective lateral force decrease has been developed.

1. Introduction

To shorten traveling times for passengers of meter gauge lines in Japan, it is very important for trains to be able to run faster through sharp curves. However, running faster in curved sections tends to increase the lateral forces exerted on the track through the point of contact between wheel and rail [2]. Many problems arise from the increased lateral force in curved sections such as derailments, or wear of wheel and rail. For such reasons, it is an indispensable technology to improve curving performance of bogies for speed-up on meter gauge lines [3].

In order to decrease the lateral force in curved sections of the railway vehicles, a steering bogie system that is able to be applicable to the bolsterless bogie was designed. It is a simple steering bogie system that does not adopt complex bogie structure as referred in [4] and [5]. Actuators are installed between the axle boxes and the bogie frame, extend the outer side wheel base on curved section, and turn the wheel-sets to the tangential direction of a curved track. This steering system is applied to the bogie that has mono-link type primary suspension. The mono-link with the actuator function is installed in place of the ordinary mono-link, and adds an appropriate supplemental steering force to self-steering characteristic of the wheel-sets. The maximum stroke of the actuators is limited according to the arrangement of the track and the other requirements. The authors have designated this system as an “assist steering system.” In this paper, we report the result of fundamental running test in the test line and bench tests.

2. Assist Steering System Composition

2.1 Test Bogie

The following two methods are devised when assuming steering force is added to the bolsterless bogie. One method installs the actuator between the car-body and the bogie frame, and gives the appropriate steering force to the bogie frame turning direction [6]. Another method gives the steering force between bogie frame and axle boxes, to operate the wheel-sets against the tangential direction of the curve. In this paper, the actuator was installed between the bogie frame and the axle boxes because the actuator composition is simpler.

In Japan, axle beam type primary suspension has been adoptable for many cases in recent years [7], in this paper; mono-link type primary suspension was examined as a test bogie. If the actuator function is given to the mono-link, the assist steering bogie can be composed within the few ranges of remodeling in the bogie because the steering force can be simply given between the bogie frame and the axle box. Moreover, assist actuator needs not to bear the bending moment that caused by the axle box lateral displacement in the mono-link type primary suspension, so the assist actuator can compose more easy. External view of bogie that used for the test of assist steering system is shown in Figure 1 and the mono-link installation state are pointed out by circular.
2.2 Geometric Study in a Curve Section

To work out basic specs of the assist actuator, curve section behavior of geometrical displacement of the axle box against to the curvature was examined. Displacement was calculated from the essential condition for the wheel rotate direction should steer to the tangential line of the curve section in each radius (perfect steering). The inside and outside axle boxes are operated completely by the inversed phase as a precondition, and the offset movement according to the thrust transmission was assumed not to cause. Figure 2 shows the relationship of the curve radius and the longitudinal displacement of axle boxes.

This longitudinal displacement means the situation that the inside and outside axle boxes operate in the opposite direction each other. The actuator specification that can confirm the effect of the lateral force decrease in curve radius 100m from the test line alignment, the maximum actuator stroke was assumed to be 10mm. That stroke is the half of perfect steering condition and the effect of assist steering was confirmed by the numerical simulation that carried out in advance.

2.3 Structure of Assist Actuator

The rubber bellows was applied to the assist actuator as a pneumatic actuator, and give the steering force in one-way expansion direction was designed. Rubber bushings were inserted at the both ends of the mono-link and compound of two rubber bushings stiffness and the primary suspension spring longitudinal stiffness becomes a total longitudinal stiffness of primary suspension of the mono-link type bogie. In this system, the case of the controller system failure or damage of the rubber bellows, the longitudinal stiffness of primary suspension could not support by the assist actuator that was equipped instead of the mono-link, so the bogie running stability would not secure. Considering these situations, pre-loaded spring was installed in parallel with the rubber bellows.

Cross section of the mono-link built in actuator that has been developed for the running tests is shown in Fig. 3. The assist steering actuator works as a usual mono-link suspension with normal longitudinal stiffness by the pre-loaded spring when the controller operation is not active or the controller is failed, thus this system does not affect to the bogie running stability. In addition, this feature contributes to fail-safe function for a mechanical trouble like the explosion of the rubber bellows that is used for actuator. Pre-loaded spring force is set up to a larger force than the obstacle force that cause at usual running condition, so the actuator will not expand while the steering controller is inactive. The total length of the actuator is expanded with more compression of pre-loaded spring at actuator operation. Pre-loaded spring was judged to be an appropriate composition of the viewpoint of fail-safe function, in spite of the loss of the actuator generated force. Table 1 shows the principal specs of the actuator made for running tests.

Such an assist actuator was substituted for the mono-link, it installed in each primary suspension, and test run was carried out. Two actuators that installed outer rail side are expanded outer rail side wheel-base and steer the wheel-sets when the bogie is running on a curve section. The proportional valve that compensates deflection between target pressure and the real inner pressure by mechanical feedback was used for a pneumatic control valve for the actuator.
2.4 Assist Steering Controller

Two method of assist steering controller system were examined and carried out running tests. One method is predictive controller with track alignment and running position detective device, another is independent controller that uses internal sensors.

Predictive controller. In Japan, predictive control method is practical used for controlled tilting train system [8]. Controller detects present running position from absolute position information that is obtained from ATS (Automatic Train Stop) signal sensing and accumulation of axle driven generator pulse. It was examined to apply this system to the steering controller, to read predictive curve information from a present running position, and to generate an appropriate steering control pattern that adjusted alignment of track. It is possible to correspond to the actuator operational delay by this predictive steering control. However, controller system makes to a large scale when putting it to practical use, and the system cost also increases.

In the running tests, a reflection seat was set up on the ground side as an absolute position detection point, and the steering control was performed based on the point where the reflection seat had been detected with the optoelectronic switch on the vehicle. Assist steering control pattern was made from alignment information that obtained beforehand and installed to the steering controller.

Figure 4 shows the structure of the predictive controller and the composition of the pneumatic system. Industrial computer that is equipped with the real-time Operating System is applicable for the assist steering controller and controller’s operational situation is observed with other computer that connected Local Area Network. The assist steering force pattern is added a step gain that is similar to the tilting train control pattern in consideration of the pneumatic actuator operational delay at the time of standing up of the target steering force.

Independent controller. Independent control method generates the steering force pattern from sensor information. These sensors are internal sensor without mechanical contact to the external world such as a gyroscope or an acceleration sensor. This method cannot unite the feed forward system fundamentally; therefore, the control delay should occur from data processing time.

The independent controller estimate the curvature of running position from the car body yawing angular velocity and vehicle velocity in a real time process, and has one by one determined the target steering force corresponding to the estimated curvature. Moreover, the controller compensates the target steering force for the pneumatic actuator operational delay in the transition curve section by using differentiation elements of estimated curvature. Therefore, the controller sets steering force from two signal paths: one path is concerned with curvature and another with curvature differentiation. Figure 5 shows the structure of the independent controller and the composition of the pneumatic system. In addition, Fig. 6 shows the controller block diagram. Independent steering controller's hardware composition is basically similar to the predictive controller.
A main purpose of the assist steering control of the bolsterless bogie is basically an effect of the lateral force decrease in the circular curve section. Therefore, the system is able to contribute to the lateral force decrease when appropriate steering operation is completed until the circular curve section entrance from the transition curve section. For such reasons, the assist steering system for the bolsterless bogie that considers putting to practical use in the future, the adoption of the independent control method is expected. However, the predictive controller was carried out to running tests since the system has high degree freedom of target value for the evaluation of an appropriate steering control.

3. Results of the Running Tests

3.1 Abstract of Running Tests

The assist steering system with such features has been applicable to a test bogie, and fundamental running tests were carried out on the test line on the premises of Railway Technical Research Institute. Figure 7 shows the external view of the test train and Fig. 8 shows external view of the test bogie with the assist actuators that were installed between the bogie frame and the axle boxes. Running tests were executed on the curve that radius is 100(m), and vehicle-running speed was approximately 18 km/h at the entrance of circular curve section.

3.2 Running Test Results of Predictive Control

Figure 9 shows the measured lateral force of test train without steering control and predictive control. A horizontal axis is the running distance from the absolute position. The step gain of steering pattern has been added 60% of the maximum steering force at the entrance of the transition curve. This step gain was most effective for reducing the lateral force as a predictive control method.

Average lateral force was decreased approximately 37% on entrance transition curve and decreased approximately 24% on circular curve section by assist steering control with predictive control. In particular, the step gain addition of steering force is very effective for reducing lateral force.
on entrance transition curve section. However, when the excessive step gain was added, inner rail side lateral force changed to positive value that means over steering condition. In the 60% step gain addition, such a tendency was admissible at the position of about 20 to 30m of the inner side lateral force chart.

There are several peaks of outer rail side lateral force in the circular curve section and the effect of the lateral force reduction is not clear. It is conceivable that the pneumatic assist actuator tends to be influenced by the track irregularity, since the expanded actuator stiffness is supported only by pneumatic pressure. As for the stroke of the actuator, operation of approximately 9.5mm that was almost common in leading and second axle actuator, near the maximum stroke was confirmed.

3.3 Running Test Result of Independent Control

Figure 10 shows the measured lateral force of test train without steering control and independent control. The assist steering force pattern was output according to almost assumption, and the possibility that the independent assist steering controller method was valid to achieved without alignment of track and running position detection. Outer rail side lateral force reduction of the distance about 30m is unconfirmed compared with the result of the predictive control. However, it is thought that the possibility to be able to improve the effect of lateral force reduction with the advanced assist steering control method. The lateral force decrease rate in the entrance transition curve section and the circular curve section was 37%, 28% respectively, and it was possible to achieve the same level with the predictive control that is required more complex system.
4. Bench Tests Results and Control Method for Fail-safe Function

4.1 Outline of the bench test device

The curve radius of the above mentioned test line was 100m and the tested running velocity was approximately 18km/h from the restriction of the test line alignment and test vehicle's performance. For these reasons, more high-speed running bench tests that are similar condition to the commercial running situation were carried out on a rolling stock test stand. High speed running bench test has been executed at Bogie Test Facility in National Traffic Safety and Environmental Laboratory. This facility is able to simulate a curve section passing situation [9]. Figure 11 shows the roller rig from upper side and structure of the test plant.

1. Yawing movements of roller rigs simulate a geometric arrangement of the track.
2. Rotational speed difference between inside and outside of roller rigs by differential gear simulates the difference of the track distance.
3. Lateral movement of the holding device simulates the bogie angle. (Car body model is installed with a holding device that set up on the ground side.)

The curving behavior of the assist steering bogie is simulated by the above-mentioned cooperated three motions. Figure 12 shows the external view of the rolling stock test stand.

![Fig. 11 Simulation of a curve passing situation](image-url)
4.2 Lateral force reduction effect of the bench test

Figure 13 shows the results of lateral force reduction effect on high speed curve section passing situation [10]. The left chart shows the average lateral force of the outer side leading axle at the non-controlled condition. The horizontal axis is the running speed, and explanatory notes show the curve radius. Average lateral forces change to the value that plotted on the right chart when the assist steering control is multiplied with maximum assist steering force that the actuator inner pressure is 600kPa. In this bench test, the maximum stroke of assist steering actuator is limited to 4.5mm according to the bench test radius conditions. This maximum stroke is sufficient for a perfect steering at 300m in radius. It is necessary to adjust the actuator stroke to an appropriate length in proportion to the targeted curve radius of the commercial running situation.

The average outer side turning lateral force of approximately 70 to 90% was decreased by the assist steering control. The attack angle of the roller rig and the wheel measured from the ground side is approximately 0°, therefore the turning lateral force has decreased to the vicinity of 0kN. It was confirmed that the correlation of the attack angle and the lateral force was very close from the test results of other conditions.

![Fig. 13 Average lateral forces measured in the bench tests](image)

4.3 Control method for reverse-steering prevention

The confirmation examination was carried out from the viewpoint that the verification of fail-safe function, because the lateral force might arise when a reverse-steering operation. Figure 14 shows the average lateral force variation of circular curve section under running on 400m in curve radius, 75 km/h in running speed, and the state of equilibrium cant situation. The horizontal axis is inner pressure of the assist steering actuator, and the negative pressure express the reverse-steering condition that means expansion operation of inner side actuator of the curve direction.

It is confirmed that the lateral force is decreased greatly according to the inner pressure, when the assist steering force works to correct direction. On the other hand, about 30% lateral force composed
to the non-controlled condition was increased when the reverse-steering state was occurred at the maximum assist steering force (Actuator inner pressure is -600kPa). However, a precise upward tendency of lateral force was not confirmed in the reverse-steering control mode up to pressure about 300kPa level. (This is in the range of the half-tone dot meshing area of Fig. 14.) Here, actuator inner pressure 300kPa is fitted to the force of pre-loaded spring that was equipped in the assist actuator. Moreover, when an equal steering force is added to correct direction, the lateral force of 60% or more is decreased. Therefore, such the maximum steering force limitation is able to avoid the increase of lateral force at reverse-steering mode, and achieve a constant lateral force decrease effect at correct direction steering control. However, the effect of the assist steering control should be reduced from the effect of no steering force limitation.

![Fig. 14 Relations of average lateral force and actuator inner pressure](image)

### 5. New assist actuator and control method

The authors have developed a new control method that unites fail-safe function for reverse-steering mode and keep the lateral force decrease effect of the assist steering system. A tandem cylinder actuator that can individually control pre-loaded spring force and active generated actuator force was designed. An internal structure of the designed new method assist steering actuator is expressible as shown in Fig. 15.

The tandem cylinder that has two pistons and cylinders in series is used as an assist actuator, and pre-loaded springs are arranged in the rod side cylinder. (This side cylinder is designated as a "Pilot cylinder"). It is an advanced feature of the tandem cylinder, which generates larger force with small outside diameter. The pressure air supply to another cylinder (This side cylinder is designated as a "Main cylinder") is laid through the poppet valve that is installed in the rod end. The poppet valve closes the air port at the shrinking position of the rod, when the rod expands, the valve is opened. Therefore, the poppet valve is opened only at the actuator rod is expanded by the resultant force of the pilot pressure and external force, then pressure air flow into the main cylinder.

Figure 16 shows the generated force direction around the axle box and the assist actuator in a circular curve section [10]. Here, the self-steering force caused from creep force of a railway vehicle wheel-sets acts on the outer side actuator rod in extending direction. Oppositely, the inner side actuator is shortened by the self-steering force.

These situation means selected outer side assist steering actuator will work as an active controlled actuator. The actuator operates by the maximum steering force, when the rod is extended and the poppet valve is opened by the external force. Without the external force, pressure air is supplied to the pilot cylinder only. It does not open the poppet valve of the main cylinder, thus no active steering force will be generated. The wrong direction steering will be prevented by such a control method using the poppet valve in the rod end, and an effective assist steering, that decrease the lateral force can be achieved at the same time.
6. Conclusion

The assist steering system that is able to compose without a great remodeling for the bolsterless bogie of the mono-link type primary suspension was examined, and the following results were clarified.

1. A steering bogie can be simply composed by exchanging the mono-link to the link with the assist actuator function.
2. Expected effect of lateral force decrease is about 30% from the running test result compared with the no-controlled state in the circular curve section of approximately 100m in curve radius.
3. The average outer side turning lateral force of about 70 to 90% was decreased by the assist steering control from the bench test results that simulate circular curve section running conditions with 4.5mm maximum stroke of assist actuator.
4. By applying the newly proposed control method that use tandem cylinder actuator, the reverse-steering mode can be prevented and effective assist steering lateral force decrease can be achieved at the same time.
5. Lateral force decrease of the circular curve section and fail-safe function can be attempted low-cost by the practical development of the assist steering system with tandem cylinder.

References