Recent Developments in Vehicle Structure Technology

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In the fiscal year 2015, RTRI conducted research into around 300 themes. Among them were about 45 dealing with rolling stock, covering a wide range of practical areas such as increasing train running speeds and improving ride comfort, applied research such as running stability and vehicle crashworthiness, and finally, basic research such as elucidating the mechanisms underlying wheel wear.

This paper introduces three of these themes, namely, “A new type of bogie for reducing the risk of derailment,” “Carbody safety evaluation method for reducing passenger injury in the event of a level crossing accident” and “Small and low-cost pneumatic centering cylinder for tilting vehicles.”

Keywords: vehicle, running safety, crashworthiness, speed increase, ride comfort

1. Introduction

The number of research and development projects undertaken in the past five fiscal years by the nine vehicle-related laboratories in RTRI's Vehicle Structure Technology Division, Vehicle Control Technology Division and Railway Dynamics Division are shown in Fig. 1. Each fiscal year about 40 projects are conducted in this field, accounting for approximately 15% of the total number of 270 to 290 projects carried out each fiscal year at RTRI, as shown by the

Fig. 1 R&D projects from the nine vehicle-related laboratories in each fiscal year

Fig. 2 Breakdown of projects undertaken in Fiscal 2015

black line.

40% of the 45 vehicle-related projects undertaken in fiscal 2015 were aimed at improving safety as shown in Fig. 2, which is a trend reflected across the board at RTRI. Safety improvement projects focused on running safety and crashworthiness and diagnostic and evaluation techniques.

Over half vehicle-related projects were related to environmental issues, such as energy saving and noise reduction, and related to improving customer experience, such as higher train speed and interior comfort, which is double the proportion found in other departments at RTRI.

Of the achievements in R&D conducted by the Vehicle Structure Technology Division, this paper presents a derailment-resistant bogie, a carbody safety evaluation method for minimizing passenger injury in the event of a crash at a level crossing, and a compact low-cost pneumatic centering cylinder for a carbody tilting system.

2. Derailment-resistant bogie

The bogie was the product of the project “Improvement in safety against derailments and crashes,” which was part of the “R&D towards the future of railways” pillar program from the previous five-year Master Plan. When a vehicle runs at low speed through a super-elevated sharp curve, a relatively strong lateral force is generated due to the wheelset’s angle of attack (the angle between the wheels’

direction of travel and the rails) and an excess of cant causes the wheel load on the outer rail to decrease steadily. In addition, as the vehicle enters the exit transition curve section where the track is twisted due to cant transition, the lead wheel load on the outer rail decreases further, increasing the risk of flange climb derailment.

To overcome this problem, a derailment-resistant bogie was developed that features two unique systems. Firstly, the bogie frame deforms to follow the twist thereby limiting a reduction in wheel load. Secondly, the wheelset is steered to reduce the angle of attack thereby weakening the lateral force.

2.1 System for limiting wheel load reduction

A bogie equipped with a system for limiting wheel load reduction is shown in Fig. 3. Unlike conventional welded designs, this system's side beams are allowed to rotate about the cross beam to follow the twist in the track. The side beam bearings must meet the following requirements.

- 1) Capable of limiting rotational resistance to enable the bogie to follow the twist smoothly
- 2) Capable of limiting degrees of freedom other than rotation to ensure anti-hunting stability
- 3) Capable of resisting bending moments created by the secondary spring's unbalanced load
- 4) Capable of withstanding fluctuating load such as the vibration of a running vehicle
- 5) Must have the durability to pass general inspections

To meet those requirements, a multilayer plain bearing with dispersed solid lubricants is press fitted into each side beam and a rotating shaft on each end of the cross beam is inserted into each of the bearings. The maximum rotation angle is set to $\pm$ two degrees. This enables the cross and side beams to slide over one another to limit the bogie's rhombus deformation and ensure stability. The traction device is unique in that two Z-links are arranged, one on top of the other, to limit the cross beam's pitching due to tractive effort.

Fig. 3 Wheel load reduction limiting system

2.2 Pneumatically controlled steering system

The bogie angle linked steering truck, which is ready for practical application, offers efficient mitigation of lateral force. However, its complex linkage mechanism and high

initial and running costs kept it from being introduced widely into service. Therefore, a low-cost pneumatically controlled steering system was developed, which has small pneumatic actuators positioned between the axle box and bogie frame to assist the wheelset's self-steering function.

The steering system uses the tandem cylinder shown in Fig. 4 as its steering actuator. Pneumatic pressure in the cylinder is controlled to generate steering force in accordance with the bogie's swivel angle (bogie angle). The steering system is a fully mechanical system, consisting of a bogie angle detection unit, a pneumatic pressure control valve and a steering actuator, and is unlikely to cause a malfunction that can lead to reverse steering.

As shown in Fig. 5, the steering actuators are installed between the axle box and bogie frame and operate only in the direction in which the wheelbase extends. The actuators should be suspended using the linkage for mono-link type axle box suspension.

Fig. 4 Tandem cylinder structure

Fig. 5 Wheel load reduction limiting bogie with the steering system

2.3 Test track running tests

During the Fiscal year 2014, running tests were conducted with a prototypal bogie equipped with the wheel load reduction limiting system and the pneumatically controlled steering system (See Fig. 5), on a test track. Figure 6 shows the maximum derailment coefficients measured when the bogie was running at 15 km/h on a curve (cant: 90 mm, transition ratio: $\times 400$) with a radius of 160 m. For comparison, maximum values were measured in a circular curve section, an entry transition curve section and an exit transition curve section, i) with the rotation system disabled, ii)

Fig. 6 Effects of wheel load reduction limiting and steering systems

with the wheel load reduction limiting system enabled and iii) with both the wheel load reduction limiting system and pneumatically controlled steering system enabled. The effects of those systems were evident in the circular and exit transition curve sections, especially in the latter section where the maximum derailment coefficient was reduced roughly in half by the reduction limiting and steering systems.

3. Method for evaluating carbody safety to minimize passenger injury in the event of a crash at a level crossing

RTRI's Vehicle Structure Technology Division has been active in developing a range of methods for accurately analyzing vehicle behavior and damage in various crash scenarios with the aim of mitigating damage and injury. Making full use of those resources, this project studied how methods to evaluate vehicle safety performance through impact acceleration waveform analysis could be employed to help mitigate passenger injury.

The evaluation methods being presented here are also a product of the individual project, "Improvement in safety against derailments and crashes."

3.1 Train crash analysis

A response analysis was conducted for a scenario in which a vehicle (mass: 31 ton) crashes into a dump truck (mass: 11 ton) carrying earth (11 ton) stuck on a level crossing. Using train speed (30–130 km/h) at impact as a parameter, the contact load for both the vehicle and dump truck and the impact acceleration waveforms at the centers of the front and rear bolster beams and the cabin center floor were measured as the center of the carbody crashed into the center of the dump truck's loading body at 90°.

Figure 7 shows the crash site 250 ms after the vehicle crashed into the dump truck at 54 km/h. The foremost part of the vehicle was visibly deformed while some of the earth was propelled out of the load body. The cabin however sustained no significant deformation. The maximum measured impact acceleration for the vehicle was 70–110 m/s².

Fig. 7 Example of vehicle crash analysis (250 ms after a crash at 54 km/h)

3.2 Methods for evaluating injury to seated passengers

Passenger injury evaluation methods were developed whereby impact acceleration waveforms of the vehicle obtained in the exercise described in 3.1 were used as inputs to analyze passenger behavior and quantify injury. In the development process, a passenger seated on longitudinal seating was made to hit a partition panel two seats away and another passenger seated on transverse seating was made to hit the seat in front. In the longitudinal seating scenario (See Fig. 8 (a)), a rigid body dummy model was measured for injury values to various parts of the body using the MADYMO (Mathematical DYNAMIC Models) multibody software. In the transverse seating scenario, deformation, rotation, etc. of the seat in front were reproduced accurately using the PAM-CRASH finite element analysis software. The accuracy of the injury values obtained with those methods was verified using data from a sled test conducted using a body dummy model that was made to hit an obstacle (See Fig. 8 (b)).

Fig. 8 Passenger injury evaluation by analysis and sled test

3.3 Relationship between impact acceleration waveforms and passenger injury values

Finally, a method for evaluating vehicle safety to mitigate passenger injury (injury values to various part of the body) is discussed below.

Based on impact acceleration waveforms at various places on a vehicle obtained through train crash analysis (Section 3.1) and the passenger injury evaluation methods that took into account passenger posture and the characteristics of obstacles (Section 3.2), injury values to various parts of the passenger body were estimated. It was found that there was not always a correlation between maximum

Fig. 9 Relationship between integrated acceleration and injury values (with a passenger seated on longitudinal seating hitting a partition panel)

impact acceleration values and injury values. However, focusing on the period between the crash and the passenger body hitting an obstacle, there was a correlation between time-integrated values of vehicle impact acceleration waveforms and injury values as shown in Fig. 9. In that particular case, the head of a passenger seated on longitudinal seating was made to hit a partition panel. To keep head injury values below the serious injury threshold (HIC1000), integrated acceleration values must be kept roughly below 5 m/s.

Based on the above findings, integrated impact acceleration values can be used as an indicator in vehicle safety performance evaluation to mitigate passenger injury in various crash scenarios. The method will need to be refined further with various crash scenarios and passenger postures.

4. Compact low-cost pneumatic centering cylinder for a carbody tilting system

This system is the product of an R&D program (FY2013–FY2015) on the development of running gear that

fulfills both speed in curve and ride comfort expectations, and has been released for practical application.

4.1 Background and system overview

In recent years, for improved ride comfort in curves, an increasing number of vehicles are adopting air-spring type carbody tilting systems that do not require a special bogie. However, the system generates larger lateral carbody movement curved sections than pendulum type systems, resulting in lower ride comfort due to bumping with the lateral displacement stopper. A centering cylinder, shown in Fig. 10, was developed to limit carbody lateral movement. As shown in Fig. 11, the centering cylinder is positioned between the carbody and bogie in parallel with the lateral damper. A self-righting force to counter the carbody's lateral movement is generated by pneumatic pressure, mitigating bumps against the lateral displacement stopper. A mechanical device that controls the flow of compressed air into the cylinder is housed in the piston rod. The centering cylinder is compact and does not cost much as it does not require any control devices and sensors that need an electric power supply to operate.

Fig. 10 Centering cylinder (installed length: 430 mm)

Fig. 11 Installed position of the centering cylinder

Fig. 12 Mitigation of lateral acceleration by the centering cylinder in a curve (radius: 300 m, cant: 105 mm, speed: 85 km/h)

4.2 Performance evaluation

The centering cylinder was tested on a limited express train running at 85 km/h along the curved section (radius: 300 m, cant: 105 mm) of a conventional line. Figure 12 shows lateral acceleration waveforms obtained during the test and those measured without the cylinder. With the cylinder installed, the amplitude of lateral acceleration was around 2 Hz smaller especially in the circular curved section probably because bumps against the lateral displacement stopper were mitigated. Based on the results, the cylinder is expected to improve the ride-quality level (LT) in continuous curves by 2–4 dB.

Going forward, the centering cylinder will be will be proposed for installation not just on vehicles with air-

spring type carbody tilting systems but other vehicles where ride comfort in curves is affected by bumping with lateral displacement stopper.

5. Conclusion

This paper presented some of the major recent R&D achievements from the Vehicle Structure Technology Division. This division will continue to focus on improving running safety, crashworthiness and cabin comfort. It will also advance R&D efforts in other areas such as clarifying phenomena unique to railways, improving the accuracy of nondestructive tests and reducing maintenance requirements.

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