Recent Activities in Vehicle Technology Research and Development

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RTRI is conducting R & D with the aim of improving railway safety, reducing maintenance costs, and improving rail services by introducing higher running speeds. Approximately half of all R & D for vehicles is concentrated on safety, mainly focusing on research on running safety evaluation methods such as flange climb derailment and crashworthiness evaluation. To improve the quality of railway services for passengers, other research and development aims to improve ride comfort by reducing vibration, developing tilting technology and noise reduction. This paper gives an overview of current research and development being conducted in the Vehicle Structure Technology Division, the status of crashworthiness evaluation, and of work to improve ride comfort.

Keywords: vehicle, crashworthiness, ride comfort

1. Introduction

The Railway Technical Research Institute has been pursuing research and development to achieve a higher level of railway safety, higher quality of service by increasing running speeds amongst other goals, and to lower maintenance costs. Approximately half of all vehicle research and development relates to vehicle running safety evaluation methods aimed for example at flange climb derailment and crashworthiness evaluation. To improve the quality of rail services for passengers, RTRI has been working to improve ride comfort through the mitigation of car body elastic vibration, the development of car body tilting and other technologies, and the investigation of means to abate noise.

Of the recent research and development projects in vehicle structure technology, this paper reports on those related to crashworthiness evaluation and ride comfort enhancement.

2. Crashworthiness evaluation

The design standards for railway vehicle car body structures in Japan were formulated without crashing in mind. As such, they do not provide guidance on collision scenarios and other measures to evaluate vehicle crashworthiness. European countries and the United States however, have design standards for vehicles which encompass crashworthiness. Each of these standards, however, differ as they were drafted on the basis of each country's own railway system, accident experience and other local specifications.

While referring to the proven standards of these countries can be helpful in facilitating the study of vehicle design standards for crashworthiness in Japan, it is also necessary to consider Japan's own characteristics whilst doing so. One of the crash accident types with high priority for consideration in the process is unexpected collisions with automobiles at level crossings.

With this in mind, RTRI has been developing collision analyses and studies on a crashworthiness evaluation index to evaluate the safety of passengers in level crossing accidents.

2.1 Collision analysis

Car body structures capable of reducing passenger and crew injuries in collisions at level crossings are an important component of railway safety. In any design process for car body structures that offer high levels of safety in collisions, it is not realistic to conduct collision tests repeatedly using actual vehicles. A more practical approach is to evaluate crashworthiness using numerical analysis. In an attempt to verify and improve the accuracy of a collision analysis method, a collision test was conducted [1]. In this test, an actual-size, stainless steel, partial car body structure of a leading vehicle was crashed onto a rigid wall to gather fundamental data including the car body's impact deformation behavior (Fig. 1). Along with this, FEM simulation of the collision test (Fig. 2) was conducted, which showed the FEM simulation overall capable of accurately

Fig. 1 Collision test using an actual-size car body

Fig. 2 FEM simulation

reproducing the impact deformation behavior of the actual-size car body structure observed in the collision test.

2.2 Crashworthiness evaluation method

Using the results of statistical investigation of major level crossing accidents experienced in Japan, FEM simulation of level crossing accidents was conducted (Fig. 3) using various impact speeds, mass of obstacle and relative positions of the vehicle and the obstacle, and impact deceleration waveforms of the passenger area were calculated for each set of conditions. Using these impact deceleration waveforms, passenger safety was evaluated by the three crashworthiness evaluation methods ((1) to (3) as follows), and injury values of the dummy ((4) as follows) were calculated in passenger injury analysis (Fig. 4) [2].

- (1) Average deceleration to European standards (Limit 7.5 G)
- (2) Maximum deceleration to US standards (Limit 8 G)
- (3) Impact speed of passenger against seat in front to US standards (hereafter Secondary Impact Velocity, SIV) (Limit 40 km/h)
- (4) Maximum value on dummy's femur load (hereafter dummy injury value) (Limit 10 kN)

Comparison of the results using the evaluation indexes (1) to (3) with those of the dummy injury value (4) found that SIV, which is the integrated value of the car body deceleration, has the strongest correlation with the dummy injury value. Therefore, SIV is the most appropriate of the three for safety evaluation.

While this paper presents a simulation of a passenger in a rotating and reclining seat hitting the seat in front as the stainless steel car body collides with a dump truck, many other scenarios are possible such as those involving aluminum alloy car body structures, passengers on long seats and standing passengers. These and various other scenarios will also be studied in future work.

Fig. 3 FEM simulation of level crossing accident

Fig. 4 Passenger injury analysis

3. Improvement in ride comfort

Ride comfort in the broad sense refers to the psychological and physiological response of passengers to the vehicle environment and involves any number of conceivable factors including vibration, acceleration, noise, temperature and humidity. Ride comfort in the narrow sense refers to passenger responses to vibration and acceleration that occur as the vehicle runs. Ride comfort in the narrow sense can be classified into ride quality with vibration, ride quality while running through curves, ride quality during acceleration and ride quality in pendulum cars. Among these ride qualities, this paper discusses ride quality with vibration, specifically measures for reducing elastic vibration of the car body and recent work related to pendulum cars.

3.1 Mitigation of elastic vibration of the car body

In recent years, lateral vibration control systems have been introduced primarily on Shinkansen, helping to improve ride quality related to lateral vibration. This has put vertical vibration under keener scrutiny than ever before, prompting action to develop various mitigation measures. Vertical vibration includes vibration of the car body, which involves the deformation of the car body. While many mitigation methods were proposed for first-mode bending vibration based on the car body as a single elastic beam, measurements in recent years have revealed the existence of a number of vibration modes that accompany three-dimensional deformation of the car body. Elastic vibration of the car body can be the result of a number of factors: longitudinal level irregularity of the track when input to the car body through axle and air springs, or mass imbalance in wheelsets, for example. Possible mitigation measures to mitigate elastic vibration of the car body include reducing longitudinal level irregularity of the track and mass imbalance in wheelsets, vibration mitigation of the bogie, vibration reduction along the vibration transmission routes improving the vibration characteristics of the car body itself. Recent work focused on these measures is discussed below.

3.1.1 Vertical vibration control system

As an elastic vibration mitigation method for the car body through bogie vibration control, a variable primary vertical damper can be installed in parallel with primary springs. With vibration coming from the track, this method suppresses vertical and pitching vibration of bogies to reduce elastic vibration of the car body. The effect of this method has been confirmed in running tests [3]. Currently, another vibration suppression method is being developed, which uses variable secondary vertical dampers and vertical actuators between the bogie and car body in addition

Fig. 5 Vertical vibration suppression method

to variable primary vertical dampers (Fig. 5). In a rotation test on a rolling stock test stand using a Shinkansen-type car body, the method was proven effective in suppressing elastic vibration of the car body at and around 9 Hz and reducing vertical and roll rigid-body-mode vibration of the car body at and around 1 Hz [4].

3.1.2 Displacement-dependent rubber bush

As a method for isolating vibration from the bogie frame to the car body, a displacement-dependent rubber bush [5] for traction device or yaw damper is being developed to suppress longitudinal bogie vibration induced by the mass imbalance in the wheelsets. The displacement-dependent rubber bush has a small gap between the rubber and the pin (Fig. 6). The gap can be manufactured by skipping the bonding process between the rubber and the pin. The transmission of high-frequency and small displacement excitation forces is isolated by the gap. Running tests using a test car equipped with displacement-dependent rubber bushes for the single link and yaw damper, showed an improvement in vertical ride quality level of 3 dB or more in the center of the car body over the standard specifications. Further investigations are needed to examine for example change in properties over time, for practical application.

Fig. 6 Displacement-dependent rubber bush

3.1.3 Active mass damper

A vibration damping method that uses an active mass damper (AMD) is being developed for multi-modal vibration that causes three-dimensional deformation of the car body. The AMD consists of a moving mass supported by an air spring and a linear actuator (Fig. 7). By exciting the moving mass, the inertia force of the body dampens the vibration of the car body. The method utilizes the H^∞ control theory to offer high damping effect with fewer sensors. Excitation test using a Shinkansen-type test car body, set on a rolling stock test stand, with two AMD units installed under the floor in the center of the car body showed that the method was capable of reducing acceleration PSD peaks corresponding to the first bending mode of the car body and the diagonal distortion mode in which the cross

Fig. 7 Active mass damper

section of the car body deformed into a rhombic shape [6]. Going forward, the method's contribution to ride quality improvement will be verified in running tests.

3.1.4 Car body vibration analysis model

Accurate numerical analysis models are essential for efficiently studying mitigation methods for elastic vibration of the car body. As a simple numerical analysis model for elastic vibration involving three-dimensional deformation, an extended box-type model was proposed (Fig. 8) that handles the car body as three-dimensional elastic bodies. The model allows lateral elastic vibration of the car body to be analyzed as well, enabling a coupled analysis of vertical and lateral vibrations.

A method was proposed [7] for efficiently obtaining parameters for the model through particle swarm optimization based on the results of experiments, such as the rigidity of the three-dimensional elastic bodies that constitute the car body, the spring constant of the springs connecting the elastic bodies, the spring constant of the element connecting the wheelset and bogie frame and of the element connecting the bogie frame and car body and their damping coefficients. Calculation using the parameters obtained through the method revealed that the acceleration PSD peaks at around 1 Hz in the rigid car body vibration modes and the acceleration PSD peaks at around 10 Hz in the elastic vibration modes were accurately reproduced. Going forward, the model will be used for the development of vibration reduction devices and the prediction of their effect.

Fig. 8 Car body components of the extended box-type model

3.2 Car body tilting technology

Pendulum cars widely used in Japan tilt the car body while curving to soften the centrifugal force working on the passengers and achieve faster speeds than would be possible without the pendulum system. Despite these benefits, it has sometimes been pointed out that the tilting motion causes motion sickness. This has led to efforts to improve the pendulum control system to further improve the ride quality of pendulum cars. The related underlying technologies include accurate positioning of running cars, calculation of tilting angles taking into consideration the track curvature and motion sickness and actuators offering ideal car body tilting control.

Among them, the following paragraphs explain recent efforts for a train positioning system and the development of a new tilt control mechanism.

3.2.1 Train positioning system

As part of the process to develop practical devices for a new pendulum control system, the following subjects were studied: elimination of the influence of car body vibration characteristics and track irregularity, and accuracy improvement for train positioning using track curvature collation, running on a route not included in the track curvature data of the on-board database, and prevention of detection accuracy deterioration while running on a long straight section [8]. The study found that, by applying spatial filtering to curvature data (Fig. 9), it is possible to limit the influence of changes in track curvature over the years, car body vibration characteristics and running speed, allowing a substantial extension of intervals between complex on-board database maintenance sessions. It was also found that the influence of sections not fully compatible with curvature collation such as those not covered by the on-board track curvature database and long straight sections can be limited by switching back to the conventional cumulative distance traveled based on wheel turns. The system will be installed on actual vehicles for further accuracy verification and any required improvement and ultimate practical application.

Fig. 9 Application of spatial filtering to track curvature data

3.2.2 Tilt control mechanism with rotary actuator and anti-roll bar

The pendulum bogies are more complex in structure, having pendulum beams and rollers and other parts, than ordinary bogies, requiring more time and cost to maintain. On the other hand, a type of tilting car body which uses air springs employs a simpler bogie and is used on Shinkansen cars and other vehicles. However, the system has smaller maximum tilt angles than the pendulum-type system, which makes it difficult to substantially reduce excess centrifugal acceleration, a frequent requirement on meter-gauged railway lines with consecutive sharp curves. In addition, this type consumes a significant amount of compressed air to extend the air springs. Given the circumstances, a car body tilt control mechanism with a rotary actuator and an anti-roll bar that has a simpler structure than pendulum bogies but is capable of producing the equivalent maximum tilt angle of pendulum bogies, was developed [9]. It has a structure that applies a forced torque to the torsion bar spring of an ordinary anti-rolling device so that the tilting force can be applied to a car body. For the torque generation, it uses the motorized rotary actuator in consideration of responsiveness and compactness.

The tilting force is transmitted to the car body via the arms and the vertical links. As the mechanism can tilt as much as 5° , the air springs are disposed closer to each other laterally than on ordinary bogies. This mechanism is called “car body tilting above secondary suspension” without any pendulum beam; therefore, the mechanism has a centering actuator to reduce the lateral movement of the car body so that ride comfort is not compromised because of lateral bump stops in curves with a significant cant deficiency. A stationary tilting test using a prototypal bogie (Fig. 10) demonstrated that it was possible to tilt the car body with high responsiveness according to the target tilt pattern up to 5 degrees. 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 car body tilting mechanism.

Fig. 10 Car body tilting bogie with rotary actuator and anti-roll bar

4. Conclusion

This paper presents recent research and development projects in vehicle structure technology related to crashworthiness evaluation and ride comfort enhancement. In addition to crashworthiness, RTRI’s research and development work on safety improvement covers a wide range of areas including: vehicle running safety evaluation; crack development evaluation of bogie parts; penetrant, ultrasonic and other inspection technologies; and fire combustion phenomena estimation methods. With regards to improving the quality of rail services for passengers, RTRI has been pursuing mitigation of longitudinal train-set vibration, noise abatement measures and other challenges in addition to mitigation measures for elastic carbody vibration and car body tilting technology.

Higher levels of safety and greater comfort for passengers are common goals that railway operators continue to work towards. RTRI will therefore pursue its research and development in this direction, to meet these needs.

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