With an aim of improving ride comfort, we have worked to overcome issues related to increasing Shinkansen speed including control of lateral vibration, control of elastic vibration (vertical vibration) of the car body and curving performance. That was done by applying new technologies such as a lateral vibration control system and a car body tilt control system. Our new lateral vibration control system and new car body tilt control system using air spring stroke have achieved improvement of lateral ride comfort, reduction of lateral vibration in coupled operation of Shinkansen exclusive rolling stock and rolling stock for through service between Shinkansen and conventional lines and reduction of steady lateral acceleration when passing through curves.

Keywords: Ride comfort, Shinkansen, Ride comfort level, Lateral vibration, Car body elastic vibration, Vibration control, Car body tilt control

1 Introduction

Achieving both higher running speed and improvement of comfort (not deteriorating passenger comfort) is important when increasing Shinkansen speeds. So, with an aim of improving ride comfort of next-generation Shinkansen cars in high-speed running, we applied new technologies such as a vibration control system and a car body tilt control system to FASTECH360 high speed test trains (type E954 and E955). That way, we were able to verify the effects of those in running tests etc.

In this article, we will give an overview of development with FASTECH360 for improved lateral and vertical ride comfort and ride comfort when passing through curves.

2 Ride Comfort Issues

When increasing Shinkansen speeds, running stability of cars at high speed is of course important. But securing a sufficient level of ride comfort that is affected by vibration and acceleration of cars is important as well.

Challenges to overcome and development target levels regarding ride comfort improvement are as follows.

(1) Lateral ride comfort
   - Decrease of lateral vibration at fast running
   - Decrease of lateral vibration in tunnels
   ⇒ Target: lateral ride comfort level of 80 dB or less

(2) Vertical ride comfort
   - Decrease of vertical vibration at fast running
   - Decrease of car body elastic vibration
   ⇒ Target: vertical ride comfort level of 80 dB or less

(3) Curving performance (ride comfort when passing through curves)
   - Decrease of steady lateral acceleration when passing through curves
   ⇒ Target: steady lateral acceleration of 0.9 m/s² or less

3 Lateral Ride Comfort

In order to improve lateral ride comfort of Shinkansen rolling stock, it is important to reduce lateral vibration of cars by setting appropriate specifications for bogies. The bogie specifications must be determined with consideration made regarding conditions such as vibration characteristics for vibration caused by track displacement, vibration characteristics in relation to the forces acting on the car body caused by airflow disruption around the car body in tunnels and running stability at high speed.

In particular, we had to study more appropriate spring and damper characteristics along with lateral vibration control systems. The reason those studies were necessary is the fact that damper characteristics between car body and bogie are different for vibration caused by track displacement and for vibration by the force to the car body caused by airflow disruption.

Fig. 1 Concept of the Lateral Vibration Control System

3.1 Lateral Vibration Control System

Satisfactory ride comfort in terms of lateral vibration in high-speed running at over 300 km/h cannot be achieved only
through improvement of passive performance by optimizing bogie specifications. An active vibration control system that controls lateral vibration is also needed.

The Shinkansen vibration control systems that are deployed for series E2 and E3 trains use pneumatic actuators. While those systems did improve ride comfort, some issues such as vibration control delay inherent to pneumatic actuators and increase of air consumption still remain. Speed increases would make these issues more apparent, so we developed a new lateral vibration control system using actuators other than pneumatic actuators.

There are many types of actuators other than pneumatic actuators, such as hydraulic and electromagnetic types. After sufficient comparison of characteristics, advantages and weaknesses of those and performance checks in static tests, we adopted two types of actuators—electromagnetic direct drive (Fig. 2) and roller screw (Fig. 3).

3.2 Countermeasures for Lateral Vibration in Coupled Operation

In the Shinkansen network of JR East, coupled operation of cars exclusive for Shinkansen (series E2) and cars for through service on conventional and Shinkansen lines (series E3) is typically done. When a train runs with cars exclusively for Shinkansen lines in front and cars for through service in the rear of the train set, significant lateral vibration occurs in long tunnels at the head car of the cars for through service. Air pressure fluctuation by running in a tunnel causes this lateral vibration, and such vibration considerably deteriorates ride comfort.

The peak frequency of the lateral vibration in a tunnel (2.5 Hz) is slightly higher than the peak frequency in open sections (2 Hz). To decrease that lateral vibration in a tunnel, we took measures such as increasing the force of the vibration control system and optimizing the control method. After taking those measures, ride comfort level improved over the present level from “good” to “excellent” in evaluation results, giving us a good outlook on controlling lateral vibration in a tunnel. Measures need to be enhanced, however, for running at 360 km/h.

Fig. 4 shows the lateral ride comfort level at high speed running (365 km/h) for each car of a type E954 train set equipped with a lateral vibration control system.

Ride comfort level of all cars of the train was 80 dB or lower. That proved we could sufficiently achieve the target lateral ride comfort.

4 Vertical Ride Comfort

The vertical vibration occurring on Shinkansen rolling stock includes vertical vibration around 1 – 2 Hz and car body elastic vibration around 8 – 10 Hz. Particularly in recent Shinkansen rolling stock, car body elastic vibration affects ride comfort. Car body elastic vibration becomes apparent at the frequency near 4 – 8 Hz where the human body is sensitive to vertical vibration. Thus, in order to improve vertical ride comfort, it is imperative that we reduce car body elastic vibration together with vertical vibration. With car body elastic vibration, vertical vibration ride comfort generally tends to be 2 – 3 dB worse at the center of the car body than on the bogies of the car.

The frequency of car body elastic vibration depends on the natural frequency of the car body, but the magnitude is affected by the vibration transmission system and is related to vibration of the bogie frame (vertical vibration and pitching). Additionally, natural frequency of the car body, height at which traction device and yaw dampers are installed, distance between bogies and running speed affect the magnitude as well.
4.1 Effects of Installation Height of Yaw Dampers and Traction Devices

One of the causes of the car body elastic vibration is transmission of the vibration of the bogie frame (longitudinal vibration and pitching, in particular) through the coupling devices of the bogie and the car body (yaw dampers, traction devices, etc.). Thus, we changed the height of yaw dampers that link the bogie and the car body and the traction devices and carried out evaluation of the effect of that on vibration of the bogie frame and on car body elastic vibration.

Fig. 7 shows a comparison of PSD (Power Spectrum Density) for car body vertical vibration according to the installation height of yaw dampers.

When yaw dampers were installed higher than the center of the axle, a large vibration peak occurred around 11 Hz. When lowering the installation height to the height of the center of the axle, the vibration peak was lowered too.

However, bogies have side covers to reduce wayside noise. Yaw dampers and bogie side covers thus interfere with each other on cars for through service that have smaller body width. Bogie side covers therefore had to be partly cut to lower the installation height of yaw dampers to be closer to the height of the center of the axle. In determining the shape of the bogie side covers and the installation height of yaw dampers, we carefully considered the balance between the optimal installation of yaw dampers to reduce vertical vibration and the effect on wayside noise by cutting bogie side covers.

4.2 Status of Improving Vertical Ride Comfort Level

Fig. 8 shows the ride comfort levels of each car of a type E954 train set in high speed running (365 k/h).

\[ a_s = (1 + C \cdot \frac{W}{2})(V/\sqrt{R} - gC/G) \cdots \cdots (1) \]

Here,

C: Cant (mm)  R: Radius of the curve (m)
G: Gauge (mm)  V: Running velocity (m/s)
g: Gravitational acceleration (m/s²)  \( a_s \): Steady lateral acceleration (m/s²)
1 + C \cdot W: Car body tilt coefficient (increase coefficient of the acceleration of the tilting car body caused by spring deflection of the bogie, approx. 1.25 for series E2 cars)
In order to improve vertical ride comfort, we designed vertical springs of the bogies for FASTECH360 to be as soft as possible. That lowered the rolling rigidity of cars compared to that of present cars and increased the car body tilt coefficient. In order to decrease the steady lateral acceleration and rolling vibration when passing through curves that became a concern with those changes, we introduced anti-rolling devices to enhance the rolling rigidity of cars.

5.2 Car Body Tilt Control System

We traditionally set a target of 0.8 m/s² steady lateral acceleration as that allowable in terms of ride comfort. But, along with recent increases in Shinkansen speed, we have been reviewing the allowable value under the assumption that the passenger rides seated. Other JR Group companies accept approx. 0.95 m/s² for Shinkansen rolling stock. For FASTECH360, we set 0.9 m/s² as the allowable steady lateral acceleration.

As series E2 Shinkansen trains run at a maximum speed of 275 km/h on curves of 4,000 m radius and 155 mm cant, the steady lateral acceleration when passing through curves is approx. 0.6 m/s². But, FASTECH360 runs at 320 km/h in such curves, so the steady lateral acceleration when passing through curves will be 1.2 m/s² if the car body tilt coefficient of FASTECH360 is equal to that of series E2, thus exceeding the allowable value.

As an approach to reduce steady lateral acceleration, we introduced a car body tilt control system. That makes cars lean to the inside when passing through curves.

at high speed on large curves, we set a maximum car body tilt control angle of two degrees and adopted a one-side lift system using air spring stroke that needs only minimal additional equipment. Fig. 10 shows the concept of that system.

The car body tilt angle that a car with a car body tilt control system requires to achieve 0.9 m/s² or less steady lateral acceleration when passing through curves can be found by formula 2 below.

\[
0.9 \text{ m/s}^2 = \left(1 + C \phi \right) \left(\frac{V}{R} - \frac{gC}{G} - g \theta \right) \cdot \cdot \cdot \cdot (2)
\]

Here,
C: Cant (mm)
G: Gauge (mm)
V: Running velocity (m/s)
g: Gravitational acceleration (m/s²)
\( \theta \): Car body tilt angle (rad)
1 + C \phi: Car body tilt coefficient

The aforementioned formula shows that the maximum speed at which a train can run on a curve of 4,000 m radius and 155 mm cant within the allowable steady lateral acceleration under the condition of two-degree car body tilt angle is 330 km/h (320 km/h for 1.5-degree car body tilt angle).

As we designed vertical springs of FASTECH360 to be soft for ride comfort, large rolling vibration occurred when passing through curves at high speed even when using the anti-rolling device, and that deteriorated ride comfort. In order to decrease that rolling vibration and improve ride comfort, we adjusted the balance between securing the car body tilt coefficient and controlling car body tilt by enhancing the rigidity of the anti-rolling device. Still, continued study of rolling vibration control is required for further speed increases.

6 Conclusion

In an aim to improve ride comfort of next-generation Shinkansen rolling stock, we adopted a new lateral vibration control system and new car body tilt control system and reconsidered the damper location. That allowed us to improve lateral and vertical ride comfort and ride comfort when passing through curves, and it gave us a good outlook on achieving ride comfort in the planned 320 km/h maximum operating speed range of next-generation Shinkansen rolling stock. Those achievements have been applied to next-generation series E5 Shinkansen trains.

We will continue to go forward with development to achieve better ride comfort performance even at higher operational speeds. In particular, we will work on development related to car body vertical vibration decrease, improvement of ride comfort when passing through curves and reduction of lateral vibration in tunnels.

Reference: