Rear-wheel Independent Steering System

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Rear-wheel steering in automobiles is a function to assist vehicle stability at midium to high speed driving as well as improve cornering at low speed driving and is already installed in some luxury-class models. NTN announced the “Rear-wheel Independent Steering System” that utilizes steer-by-wire technology for electronically-controlled steering in 2013, and has made further enhancements for even better response and a more compact, lighter weight design. This report introduces the “Rear-wheel Independent Steering System” that is capable of toe angle control with a one body combined-type steering system.

1. Introduction

Four wheel steering (4WS) systems have long been known for improving driving stability by steering the rear wheels.

4WS systems were introduced into the market in the 1980s and later rear wheel steering by mechanical means was introduced. Unfortunately, drivers may have felt uncomfortable by the lag in the transmission of power. However, recent developments in electronic components and control technologies have made it possible to steer the wheels by motor drive. Because of the improvement in responsiveness, it is now possible to eliminate this uncomfortable feeling; consequently, this technology is being adopted, especially in luxury vehicles for enhanced driving stability.

Four wheel steering is a steering system to steer the rear wheels along with the front wheels depending on the driving patterns, and is classified into the modes shown in Fig. 1. The characteristics of each mode are as follows:

(1) In-phase
Mainly used in the mid/high speed range. The rear wheels are steered in the same direction as the front wheels when turning, to improve the stability and maneuverability for changing lanes and reduce cornering.

(2) Anti-phase
Mainly used in the low speed range. The rear wheels are steered in the reverse direction of the front wheels when turning to make the turning radius smaller.

(3) Toe-in
The front side of the rear wheels is steered inside (when the distance between the front sides of both tires is compared to the distance between the rear sides of both tires, the rear distance is wider). It improves the vehicle’s straight line stability.

(4) Toe-out
The front side of the rear wheels is steered outside (when the distance between the front sides of both tires is compared to the distance between the rear sides of both tires, the front distance is wider). Not usually used.

NTN developed steer-by-wire steering system for front wheels in 2011 1) and now applies this technology for developing rear wheel independent steering system capable of controlling each of the above mentioned modes.

In this paper, we will report the system configuration and results of the vehicle test.

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2. System overview

2.1 Structure

This system, which steers the rear wheels according to the angle of the steered front wheels, makes it possible to achieve in-phase and anti-phase steering control, as well as independent toe angles for left and right rear wheels by adopting an independent and symmetrical linear motion mechanism for the left and right wheels, as shown in Fig. 2. In addition, as shown in Fig. 3, since it can be installed on the chassis, there is no impact on the driving/riding comfort level due to the change of unsprung weight.

The linear motion mechanism uses hollow DC brushless motors for compactness, and the motor torque is transmitted to the trapezoidal screw through the planetary gear reducer to drive the rotation-restrained steering shaft.

The detailed internal structure is shown in Fig. 4 and 5. A large thrust external force (lateral withstand load) generated by stationary steering etc. is received by the needle thrust bearings located in the central part. The rolling motion in the radial direction is suppressed by the sliding bearings installed at the tips of the steering shaft and the trapezoidal screws, and...
the needle radial bearings supporting the outer diameter of the material that works as the carrier for the trapezoidal screw and the planetary gear. There is no displacement of the trapezoidal screw due to the thrust external force (lateral withstand load) since the efficiency for the reverse input to the trapezoidal screw is low. In addition, resin is used as the material for the planetary gear for quietness.

In addition, a resolver is used for controlling the motor. Furthermore, the flux changed due to the movement of magnets installed on the steering shaft is detected by the Hall effect IC to determine the absolute position of the steering shaft.

2.2 Specifications of the actuator

Table 1 shows the actuator of this system. The lateral withstand load is 3.5 kN or more on one side and is capable of addressing the upper medium to executive class of vehicles of around 4.9 m in total length.

Fig. 6 shows the measurement results of the relation between the lateral withstand load and shaft speed of the steering shaft. It can achieve a shaft speed of 30 mm/s or more with 2.5 kN of lateral withstand load.

<table>
<thead>
<tr>
<th>Item</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Linear-motion method</td>
<td>Trapezoidal screw</td>
</tr>
<tr>
<td>Shaft motion level</td>
<td>±7 mm (max. motion level ±10 mm)</td>
</tr>
<tr>
<td>Motor</td>
<td>Brushless DC12V</td>
</tr>
<tr>
<td>Rotation sensor</td>
<td>Resolver (4X)</td>
</tr>
<tr>
<td>Reducer</td>
<td>Planetary gear reducer mechanism</td>
</tr>
<tr>
<td>Shaft absolute position detection</td>
<td>Hall IC</td>
</tr>
<tr>
<td>Lateral withstand load (one side)</td>
<td>3.5 kN or more</td>
</tr>
<tr>
<td>Maximum steering angle</td>
<td>±2.5 degrees</td>
</tr>
<tr>
<td>Maximum feeder speed</td>
<td>30 mm/s (at lateral withstand load of 2.5 kN)</td>
</tr>
<tr>
<td>Mass</td>
<td>9 kg</td>
</tr>
<tr>
<td>Case size</td>
<td>φ81×375mm</td>
</tr>
</tbody>
</table>

2.3 Control system

The control system consists of two ECUs which control the respective motor, as shown in Fig. 7. Two ECUs receive the target values of the steering angles according to the vehicle status from the upper ECU and determine the positions of each motor by PWM control.

These two ECUs have the functions of mutual monitoring and partial redundancy to increase safety.

3. Rear wheel steering control method

In order to confirm the effect of this system with the actual vehicle, “Vehicle speed response type front wheel steering angle proportional control” 2), which is the typical control law when rear wheel steering is added to a vehicle, was adopted. In this paper, we will describe this effect from the basic motion properties of the vehicle against the steering operation.

The degree of freedom for the vehicular motion generated from steering is lateral, yawing and rolling, however, we can ignore rolling as the vertical movement is a secondary motion and if we set the following assumptions, we can consider the motion of a vehicle running at a constant speed in the horizontal $X−Y$ plane shown in Fig. 8.

- Vehicular traveling velocity is constant
- Tire properties of the left and right tires are the same
As mentioned above, the basic vehicular motion equation in a horizontal plane ignoring rolling can be expressed as follows:

\[ mV \left( \frac{d\beta}{dt} + r \right) = Y_f + Y_r + Y_f + Y_r \quad \text{(1)} \]

\[ I \frac{dr}{dt} = l_f (Y_f + Y_r) - l_r (Y_f + Y_r) \quad \text{(2)} \]

where,

- \( \beta \): Lateral slip angle of the vehicular center of gravity
- \( V \): Vehicular traveling velocity
- \( m \): Inertial mass of the vehicle
- \( Y_{xx} \): Cornering force given to tires
- \( r \): Yaw angle velocity
- \( l \): Yawing inertial moment of the vehicle
- \( l_f \): Distance between the vehicular center of gravity and the front shaft
- \( l_r \): Distance between the vehicular center of gravity and the rear shaft

If we assume that there is no difference between the properties of the left and right tires themselves, then there is no difference in the cornering forces felt by both tires. Therefore, if we set the cornering force of the front and rear tires as \( Y_f \) and \( Y_r \), respectively, we get the following equations:

\[ 2Y_f = Y_f + Y_f \quad \text{(3)} \]

\[ 2Y_r = Y_r + Y_r \quad \text{(4)} \]

By considering this force to be the force on the \( y \) direction in Fig. 8, equation (1) and (2) can be written as follows:

\[ mV \left( \frac{d\beta}{dt} + r \right) = 2Y_f + 2Y_r \quad \text{(5)} \]

\[ I \frac{dr}{dt} = 2l_f Y_f - 2l_r Y_r \quad \text{(6)} \]

When the lateral slip angle is small, the cornering forces acting on the tire \( Y_f \) and \( Y_r \) are proportional to the lateral slip angles of the front and rear tires \( \beta_f \) and \( \beta_r \). By taking the counterclockwise angle positive, the cornering force, when the lateral slip angle is positive, can be written as follows, since the cornering force acts on the negative \( y \) direction in Fig. 8:

\[ Y_f = -K_f \beta_f \quad \text{(7)} \]

\[ Y_r = -K_r \beta_r \quad \text{(8)} \]

where,

- \( K_f \): Front wheel cornering power
- \( K_r \): Rear wheel cornering power

In the above equations, when a small steering angle is given to the front and rear wheels, the lateral slip angle of the front and rear tires \( \beta_f \) and \( \beta_r \) can be approximated as follows:

\[ \beta_f = \beta + \frac{l_f}{V} r - \delta_f \quad \text{(9)} \]

\[ \beta_r = \beta - \frac{l_r}{V} r - \delta_r \quad \text{(10)} \]

where,

- \( \beta_f \): Front wheel steering angle
- \( \beta_r \): Rear wheel steering angle

Assigning equations (9) and (10) to equations (7) and (8), the cornering force can be expressed as follows:

\[ Y_f = -K_f \left( \beta + \frac{l_f}{V} r - \delta_f \right) \quad \text{(11)} \]

\[ Y_r = -K_r \left( \beta - \frac{l_r}{V} r - \delta_r \right) \quad \text{(12)} \]

By assigning equations (11) and (12) to equations (5) and (6), the following motion equations can be obtained:

\[ mV \left( \frac{d\beta}{dt} + r \right) + 2(K_f + K_r) \beta + \left\{ mV + \frac{2}{V} \left( l_f K_f - l_r K_r \right) \right\} r = 2K_f \delta_f + 2K_r \delta_r \quad \text{(13)} \]

\[ 2 \left( l_f K_f - l_r K_r \right) \beta + I \frac{dr}{dt} + \frac{2}{V} \left( l_f^2 K_f + l_r^2 K_r \right) r = 2l_f K_f \delta_f - 2l_r K_r \delta_r \quad \text{(14)} \]

The above equations are the basic motion equations describing the vehicular motion for the front and rear wheels in the horizontal plane.

“Vehicle speed response type front wheel steering angle proportional control” adopted with the vehicular tests, the front steering angle and rear steering angle can be written as follows:

\[ \delta_f = \frac{\delta}{n} \quad \text{(15)} \]

\[ \delta_r = k \delta_f = \frac{k}{n} \delta \quad \text{(16)} \]
4.2 Response evaluation

The test was conducted in the double lane change course with a dry surface, as shown in Fig. 10, with the vehicle entering the course at the speed of 70 km/h and maintaining the speed as constant as possible, and the yaw rate and lateral acceleration against the steering angle were recorded. Fig. 11 shows the results.

When the rear wheel steering function is OFF (Fig. 11 (a) and (c)), there will be a delay in the trackability of the yaw rate and the lateral acceleration against the steering angle requiring the driver’s unnecessary steering manipulation. On the other hand, when the rear steering function is ON (Fig. 11 (b) and (d)), the rear wheels turn approx. 1.5 degrees in-phase with the front wheels at 70 km/h. As a result, it is revealed that the linearity of lateral acceleration and yaw rate with respect to the steering angle are improved. This means that the driver is operating the vehicle as desired, with improved trackability of the yaw rate and lateral acceleration against the steering handling, proving the effect of the rear wheel steering for driving stability.

With actual vehicles, there is a difference between these quantitative data and the feeling that the drivers sense when steering. By applying various tunings at the vehicle level, we are ready to develop this technology by leveraging the advantages of 4WS that contribute to driving stability.

4. Vehicle test

4.1 Test vehicle and driving conditions

We installed this system in the test vehicle with the specifications shown in Table 2 and conducted driving tests on the test course. We used “Vehicle speed response type front wheel steering angle proportional control” described in the previous section to determine the rear wheel steering level according to the front wheel steering angle and the vehicle speed, and evaluated the vehicle response under actual driving.

![Fig. 9 Steering angle ratio](image)

![Table 2 Specifications of test vehicle](table)

<table>
<thead>
<tr>
<th>Item</th>
<th>Specification</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vehicle size</td>
<td>4940×1940×1500 (LxWxH mm)</td>
</tr>
<tr>
<td>Weight</td>
<td>Approx. 1700 kg</td>
</tr>
<tr>
<td>Drive method</td>
<td>Rear wheel drive</td>
</tr>
<tr>
<td>Rear-wheel max. steering angle</td>
<td>±2.5 degrees</td>
</tr>
<tr>
<td>Rear-wheel max. steering speed</td>
<td>10 degrees/s (axial force: 2.5 kN)</td>
</tr>
</tbody>
</table>
5. Conclusion

In this paper, we introduced the “rear wheel independent steering system”. With actual vehicle tests, we have confirmed the effect of the in-phase mode, however, since this system is able to independently and proactively control the toe angles of the left and right wheels regardless of the suspension structure, it is possible to apply various steering controls according to the driving conditions. By using these features, it is expected that toe-in for improved driving stability and anti-phase mode for automatic parking, etc. are expected to be applied.

Along with the electrification of vehicles, the adoption of by-wire technology and the development of autonomous vehicles, market expansion of these module products to contribute to the performance enhancement of safety, stability and convenience is expected to continue. To be prepared for further development of the electrified modules including vehicle control technologies, we strive to develop new module/system products that contribute to the electrification, improved fuel consumption and enhanced driving performance of vehicles.

References