Hub Bearing Module with Steering Function for Rear Wheel

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We have developed a hub bearing module, 'Ra-sHUB' with steering function incorporating the steering angle adjustment mechanism in the hub bearing. This product can be attached to rear driven wheels, by controlling the right and left wheel with separate actuators, we can control the angle of the right and left wheel independently. Therefore, the dynamic performance of the vehicle is significantly improved.

1. Introduction

There are Systems available that improve turning capabilities at low driving speeds and enhance vehicle stability at medium to high driving speeds by making corrections to the steering angle of the wheels to suit the vehicle's driving conditions.

NTN developed the "Hub Bearing Module with Steering Adjust Function[2)-4)](sHUB™)" that turns the front wheels by incorporating a steering function into the "Hub Bearing[1)]" of which **NTN** has the leading global market share.

NTN has verified in a number of actual driving tests that independently correcting the steering angle of the left and right front wheels can improve the driving performance of vehicles in a range of situations, from ordinary driving to harsh driving conditions, as well as from very low driving speeds up to high speeds.

The shape and configuration of each part has now been modified so that this system can be assembled to the rear wheels. This report covers the basic performance test and actual driving test that were conducted.

Conventional rear wheel steering systems have been limited to suspension structures such as multi-link systems, and large operating angles were difficult to achieve due to the structure of the system. The Hub Bearing Module with Steering Function for Rear Wheel (hereafter, Ra-sHUB) incorporates a steering shaft in the hub bearing for an integrated steering angle adjustment mechanism, with its compact design meaning it can be assembled in the same way as conventional hub bearings.

The result can be applied as a rear wheel steering system capable of large operating angles that can even be assembled to rigid axle systems such as torsion beams, regardless of the suspension structure.

2. Background

Rear wheel steering systems first became available in mass-produced vehicles in the 1980s, however many commented on the unnatural way the vehicle behaved with the driver's steering operation. The advances that have been developed to control technology prove this unnatural feeling can be minimized, and such systems have increasingly been used in luxury cars and sports cars in recent years.

Rear wheel steering systems have the following advantages.

- Low-speed cornering
  Turning the rear wheels in the opposite direction (reverse phase) to the front wheels reduces the turning radius, allowing tighter turns to be made in the same way as a vehicle with a shorter wheelbase.
- High-speed cornering
  Turning the rear wheels in the same direction (same phase) as the front wheels and controlling the centrifugal force to reduce the yaw moment achieves the same level of stability as vehicles with a longer wheelbase.
- Better fuel efficiency
  Vehicles generally have rear wheels set to toe-in to increase stability during braking, however this increases running resistance and in turn reduces fuel efficiency. Reducing running resistance with the tires parallel to the driving direction during ordinary driving, and changing to toe-in when braking can help achieve both safety and low-fuel consumption driving.

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3. Concept

The aim of control with Ra-sHUB assembled to the rear wheels is to increase the dynamic performance of the vehicle, as well as achieving safe, comfortable and energy-efficient driving. The system is also anticipated to be used with future automated driving technologies. The main concepts are as outlined below.

① Assembled on the left and right rear wheels for independent control of steering angles. This allows each wheel to be controlled at the optimum angle to suit driving conditions
- Energy-efficient driving with minimal cornering drag
- Excellent response and stable vehicle stance even during emergency situations like hazard avoidance

② Can be assembled to existing vehicles without requiring any modifications, regardless of the type of suspension system

③ Small and lightweight due to optimized internal design

④ Assembled within wheels to maintain vehicle design flexibility

Fig. 1 shows Ra-sHUB assembled to a vehicle's rear wheels. The Ra-sHUB controller separately calculates and controls the target angle of the left and right Ra-sHUB based on vehicle information such as speed and angle of the steering wheel.

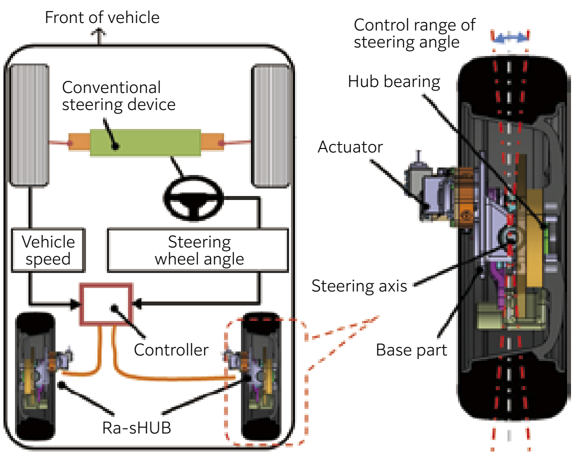

Fig. 1 Vehicle image with Ra-sHUB (Attached to rear wheels)

Fig. 2 shows the layout with Ra-sHUB assembled to an ordinary rigid axle (torsion beam). Turning the rear wheels when a rigid axle is used generally requires movement of the entire rigid axle, however, a rear wheel steering system can be achieved easily by attaching Ra-sHUB to the hub bearing mounting face of the torsion beam.

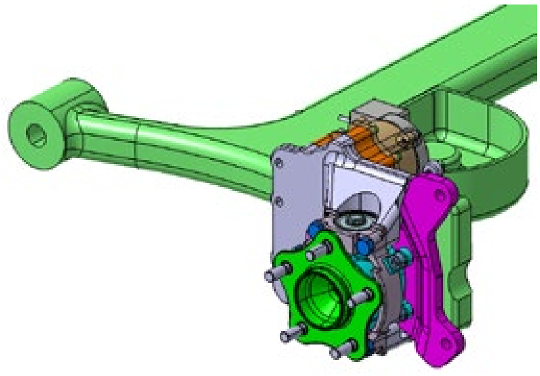

Fig. 2 Ra-sHUB attached to rigid axle

The basic layout of the rear wheel with Ra-sHUB assembled is shown in **Fig. 3**. When all four wheels of the vehicle are in equal contact with the ground, the steering axis is slightly behind the point of contact between the tire and ground. This results in ground contact point located forward of the steering axis, so when the reverse input load from the ground contact point acts on the outside tire of the turn when cornering, the large load applied to the outside tire forces it toward a natural toe-in direction, which increases the cornering limit performance for more stable driving.

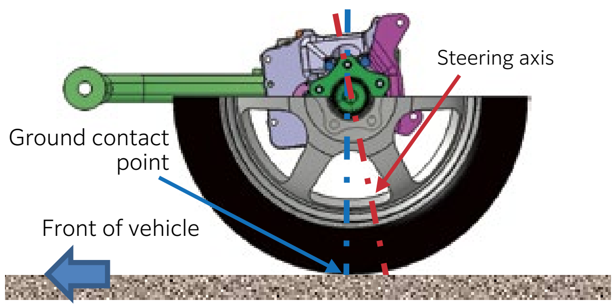

Fig. 3 Layout of rear wheel with Ra-sHUB

4. Configuration and Specification

4.1 Components

Fig. 4 shows the components of Ra-sHUB. Ra-sHUB is comprised of three core components: an actuator, base part, and hub bearing. The role of each component is as follows.

- Actuator : fixed to the base part, and consists of a motor, reducer and trapezoidal screw for steering the hub bearing.
- Base part : connects to the suspension system of the vehicle.
- Hub bearing : supports the base against rotation around the rotation axis and around the steering axis of the wheel.

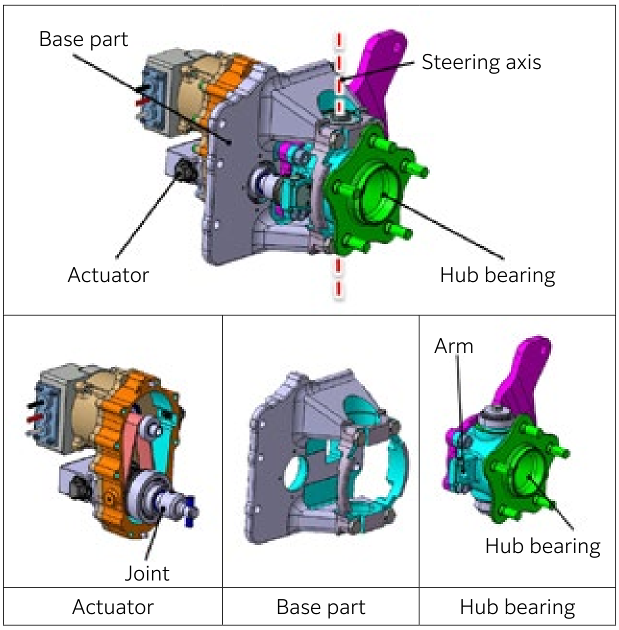

Fig. 4 Components of Ra-sHUB

The motor of the actuator is controlled at the best tire angle by the controller based on the input such as the vehicle speed and steering wheel angle. The rotation from the motor is converted to linear motion by the trapezoidal screw via the reducer, and the screw drives the end of the arm via the joint to steer the hub bearing around the steering axis.

The reverse input load from the tires is also blocked by the self-lock mechanism of the trapezoidal screw, which helps to reduce motor power consumption.

4.2 Specifications

Fig. 5 shows the appearance of the developed product designed for the rear wheels of a front-wheel drive C segment vehicle (with torsion beam rear suspension structure). The specifications of the developed product are shown in **Table 1**.

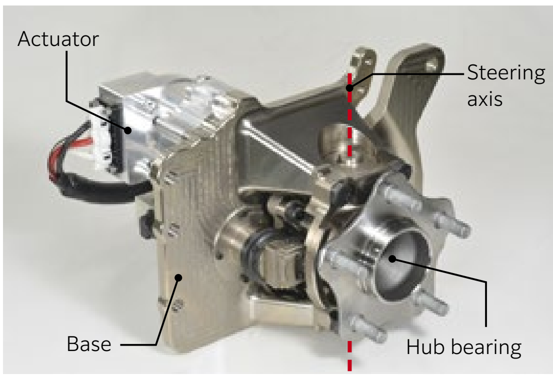

Fig. 5 Prototype of the Ra-sHUB (Left rear wheel use)

Table 1 Specifications of the Ra-sHUB prototype

Item	Values
Maximum steering torque	350 Nm
Power supply voltage	24 V
Maximum steering angle	± 3.5 deg
Maximum steering angular speed	16 deg/s

5. Basic Performance Test

The basic characteristics of the developed product required for assembling it to vehicles were verified.

5.1 Frequency Response

A frequency response characteristics test was conducted with the wheels of a test vehicle (in a stationary state) assembled with Ra-sHUB placed on a turntable. The response of the actual steering angles was verified by applying a steering angle command in the form of a 0.5 degree amplitude sinusoidal wave to Ra-sHUB and changing the frequency.

The test results are shown in **Fig. 6**. At frequencies of 4 Hz or less, the amplitude gain (shown as the log of the ratio between the amplitude value of the actual steering angle and the command value, **Fig. 6** (a)) and the absolute value of the phase difference (**Fig. 6** (b)) were small, and deemed to be at a level that can be used to control the stance of the vehicle without any issues.

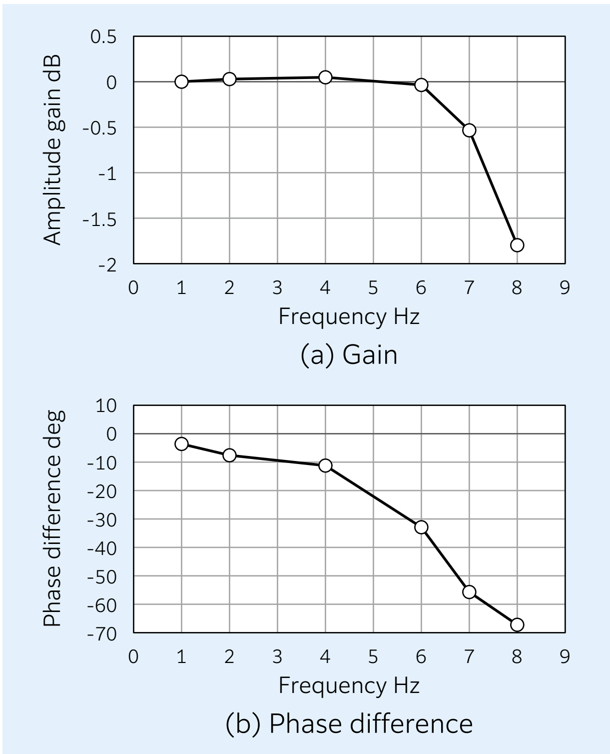

Fig. 6 Frequency response characteristic

5.2 Small Steering Angle Durability Test

Many repeated minor adjustments around the central steering position are expected during actual driving, so the durability was verified under the conditions shown in **Table 2**. **Fig. 7** shows the comparison of response characteristics before and after the durability test. There was no change in response characteristics with respect to commands before and after the test, and there was no difference in the response waveform. This verified that there was no decrease in performance even after repeated minor steering adjustments.

Table 2 Durability test condition

Steering Angle	± 0.5 deg
Steering frequency	5 Hz (sinusoidal wave)
Load from road surface	3.8 kN (equivalent to vehicle weight acting on each wheel)
No. of repeated steering cycles	10^7 cycles

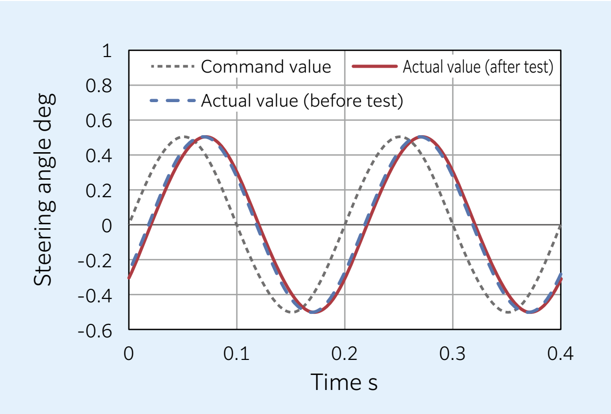

Fig. 7 Comparison of response characteristic

5.3 Temperature Characteristics

The usage temperature of the Ra-sHUB was set at the same temperature as hub bearings in ordinary vehicles at -40 to +120 ℃ . The change in steering speed within environment temperature ranges was checked. The test involved immersing the controller and sample into a constant temperature bath and kept at a set temperature for one hour before testing operation. **Fig. 8** shows the measured waveforms of steering speed at each environmental temperature.

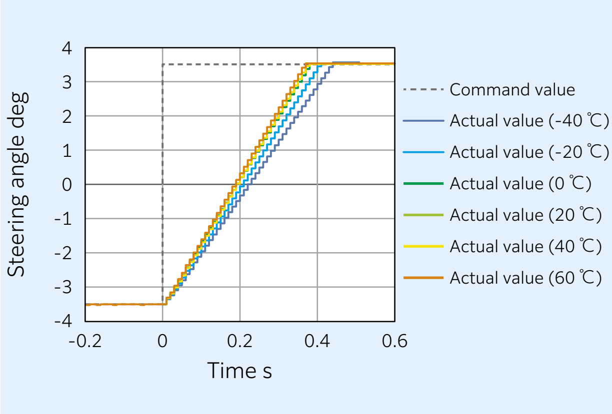

Fig. 8 Waveform of steering speed

The steering speed was determined from the actual steering angle inclination of the Ra-sHUB when applied with stepped steering commands (-3.5 ⇒ +3.5 deg (**Fig. 8** dotted line)).

Fig. 9 shows the relationship between the steering speed and environmental temperature. While a decrease in steering speed that is thought to be caused by an increase in internal resistance at low temperature ranges was observed, the design meets specifications and has minimal impact on vehicle control.

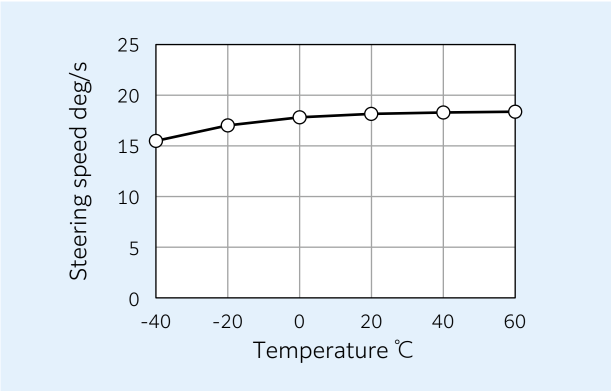

Fig. 9 Relations of temperature and steering speed

5.4 Rigidity and Strength Tests

The rigidity and strength when mounted to the vehicle was verified for factoring in external forces from the road surface when driving, by individually applying loads in the vertical direction (z direction) and the longitudinal direction (x direction), and moments around the x axis. The XYZ directions are shown in **Fig. 10**.

Fig. 11 shows the relationship between the load from each direction and displacement. There were no major differences in rigidity in the vehicle's vertical and longitudinal directions. **Fig. 12** shows the relationship between the moment load in the camber (x axis) direction and the flange inclination. No deformation or damage was observed after removing the load under all conditions.

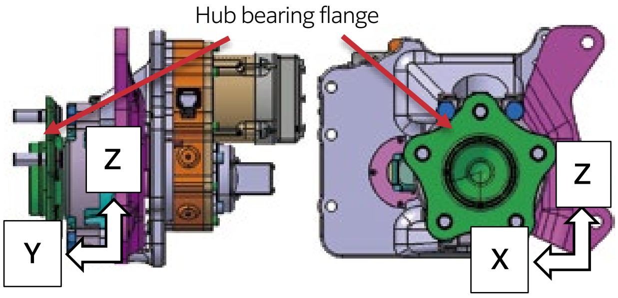

Fig. 10 Axis direction of the product

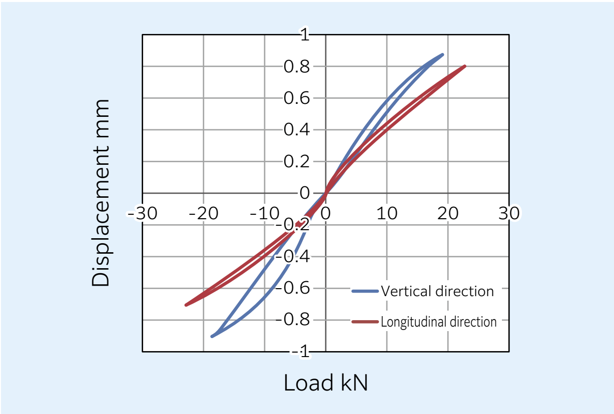

Fig. 11 Wheel rigidity

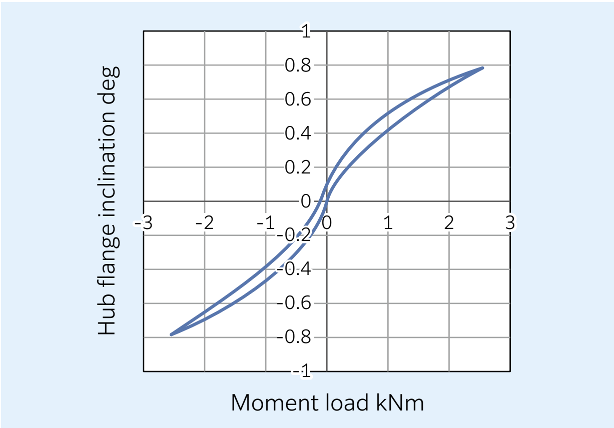

Fig. 12 Moment rigidity

6. Verification of Effective Ra-sHUB Rear-wheel Steering

To verify the improvement in vehicle cornering performance with Ra-sHUB steering, Ra-sHUB was assembled to the rear wheels (torsion beam) of a C segment test vehicle and actual driving tests conducted.

The rear wheel steering angle was changed with Ra-sHUB to suit driving conditions to control the vehicle's slip angle.

Fig. 13 shows the layout of the course on a compacted snow road used for driving tests. The test compared differences in vehicle behavior with or without Ra-sHUB steering operation while following the same line.

Data at points A to E in **Fig. 14 to 16** correspond to each of the positions A to E in **Fig. 13**.

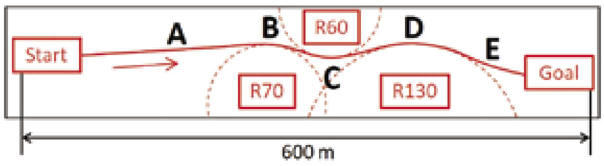

Fig. 13 Course layout

Fig. 14 shows the vehicle speed and steering wheel angle during the test, and **Fig. 15** shows the longitudinal and lateral acceleration. When driving at the same speed (84 km/h) at position B and following the same line at the tight radius position C, steering control with Ra-sHUB made cornering possible without exceeding the grip limit (0.4 G) of the tires on compacted snow roads, and there was also a 7 % rate of decrease in speed. Compared to driving without Ra-sHUB steering, the vehicle could drive through the whole course approximately 2 seconds faster.

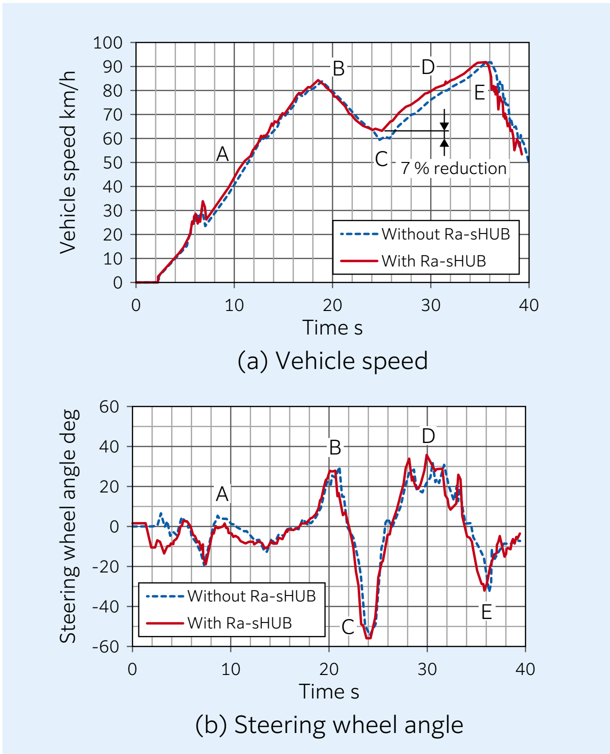

Fig. 14 Test results (Speed, Steering Angle)

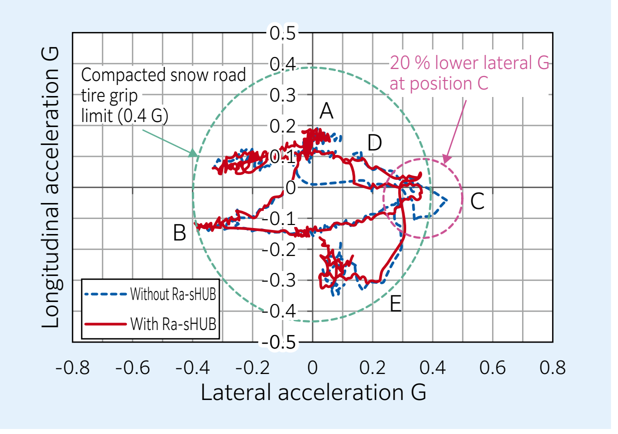

Fig. 15 Test results (Longitudinal acc, Lateral acc)

As shown in **Fig. 16**, there is a closer linear relationship between the yaw rate and steering wheel with Ra-sHUB steering compared to without Ra-sHUB steering, and the improvement in vehicle operation is clear.

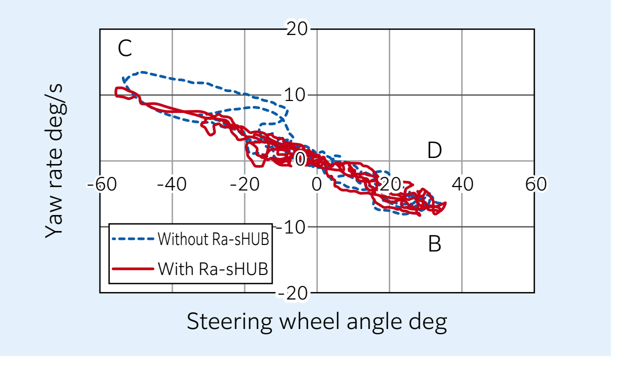

Fig. 16 Test results (Steering angle, Yaw rate)

The command value and actual angle match during this Ra-sHUB operation as shown in **Fig. 17**, and operation was observed to be in line with the command value without any delay.

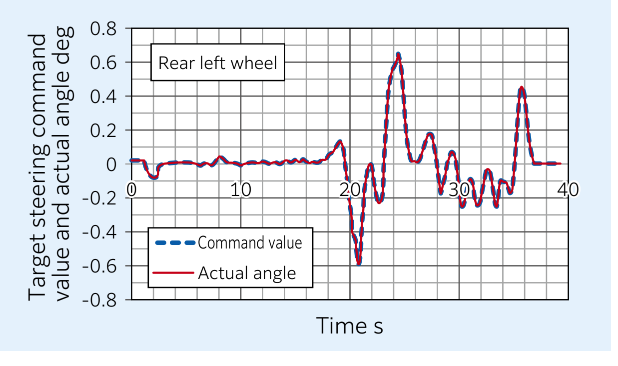

Fig. 17 Ra-sHUB command value and actual angle

The driver's workload was also estimated using the steering entropy method[5], which calculates the driver's workload from how smooth the steering angle changes.

The difference (prediction error) between the target steering angle and actual steering angle at each measurement position is calculated, with the steering entropy corresponding to the 90th percentile of absolute values of the prediction error distribution. This means that if 90 % of the data lies within the range of prediction error $\pm\alpha$ margin, the steering entropy is α. A smaller value here indicates that steering is close as possible to the ideal smoothness.

Fig. 18 shows the prediction error distribution calculated from the results of driving tests, and **Table 3** shows the values for steering entropy. This table shows that the steering entropy value is lower with Ra-sHUB steering compared to without Ra-sHUB steering, indicating that the vehicle is easier to drive by the driver and that smoother operation is possible.

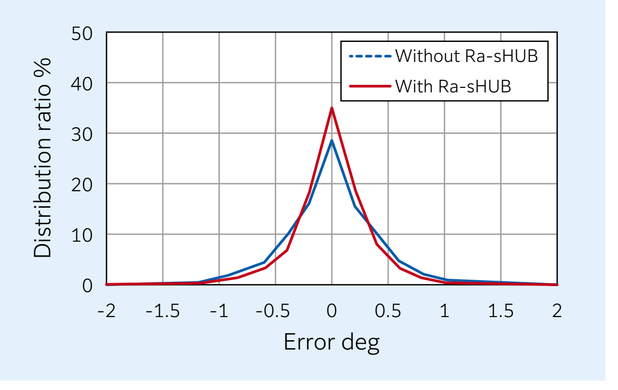

Fig. 18 Prediction error

Table 3 Steering entropy (90 percentile)

Without Ra-sHUB	With Ra-sHUB
0.73 deg	0.56 deg

7. Conclusion

This article outlines the configuration, specifications and basic performance of the "Hub Bearing Module with Steering Function for Rear Wheel."

Ra-sHUB is a system that allows rear wheel steering with large operating angles that can be assembled to rigid axle systems such as torsion beams, regardless of the suspension structure. The article outlines how Ra-sHUB is effective for improving vehicle dynamic performance and operation in driving tests conducted on compacted snow roads.

Practical applications for Ra-sHUB will be developed in the future, including compatibility with various suspension systems and further improvements in functionality.

References

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