Hub Bearing Module with Steering Adjust Function

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We have developed a hub bearing module, 'sHUB' with steering adjust function incorporating the steering angle adjustment mechanism in the hub bearing. We demonstrated that the prototype successfully modified the steering angles of the left and right wheel independently according to the driving situation of the vehicle and the operation of the driver. The developed hub bearing module will hence make a significant contribution to the dynamic performance improvement of the vehicle.

1. Introduction

In conventional vehicles the tires and the steering device placed on the front wheels are mechanically connected and therefore the turning angles of both front tires are fixed to the angle of the steering wheel being operated. When making a big turn at slow speed, the turning radii of the right and left wheels are significantly different. Therefore, in order for a smooth turn they should follow the Ackermann geometry (larger angle for the inner wheel with smaller angle for the outer wheel). On the other hand, parallel or reverse Ackermann geometry is suggested to improve the turning performance in mid to high-speed maneuvers.

The Ackermann characteristics are determined by the geometric configuration of the steering device; therefore, volume production vehicles choose to emphasize either maneuverability at low speed or turning ability at high-speed depending on the vehicle concept.

Also, the toe angle of the outer wheel, which supports a heavy load while turning at mid to high-speed, is passively controlled by the damping characteristics of the suspension bushings; however, it is more desirable to actively control the optimum steering geometry based on the turning radius and turning acceleration.

As the top manufacturer of hub bearings, **NTN** has developed a brand new "Hub Bearing with Steering Assist Function" (hereafter, sHUB®)[1)] which combines a mechanism that adjusts the steering angle of the tires on the hub bearing, for actively controlling the steering geometry depending on the driving conditions while solving the above mentioned trade-off.

sHUB provides safe and comfortable driving by controlling the left and right wheels independently to the optimum angles depending on the running conditions of the vehicle. This module system improves straight-running and cornering stability and contributes to risk avoidance in emergencies, for example when a wheel skids on a low-μ road surface. In normal driving conditions it contributes to energy saving by minimizing the cornering drag while turning in a curve. It could also be applied to avoidance maneuvering in upcoming autonomous driving vehicles.

Fig. 1 shows an overview of how sHUBs are installed on a vehicle. They can be installed on vehicles together with the existing steering devices without making large modifications to the suspension system. The controller of sHUBs independently calculates and controls the target angles of the sHUBs on the left and right wheels based on the vehicle information, such as the vehicle speed and steering angle.

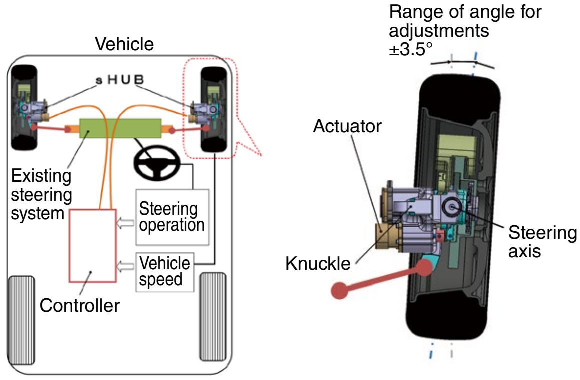

Fig. 1 Vehicle with sHUB installed (on front wheels)

2. Concept

The following parameters were set as the design concept for achieving improved vehicle dynamic performance, as well as safe and comfortable driving.

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(1) Installed on the left and right wheels in order to independently control steering angles of both wheels
(2) Optimum control to the best angles depending on the driving conditions
  • Energy saving driving minimizing cornering drag
  • Maintain vehicle stability even in an emergency situation, such as risk avoidance
(3) Able to be installed on the driven wheels (front or rear wheels) of existing vehicles regardless of the type of steering/suspension systems without requiring a large modification
(4) Compact and lightweight based on the optimum internal design

Fig. 2 shows the appearance of the prototype (for right wheel) to be used with the strut type suspension for front wheels. As shown in **Fig. 3**, the small size allows installation on both front wheels of a vehicle without modifying the surrounding structure, such as the suspension.

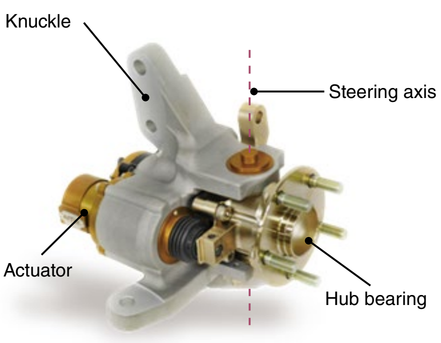

Fig. 2 Prototype of sHUB

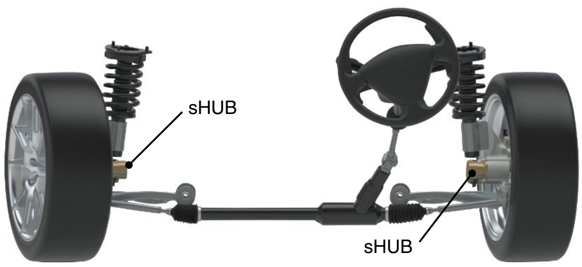

Fig. 3 sHUBs installed on front wheels

Fig. 4 shows the basic design of sHUB when it is installed on the front wheel. The kingpin axis which is the central axis of the tire during normal steering and the steering axis of sHUB are two different axes. It was designed so that those two axes cross at the ground surface. With this structure the amount of sliding is reduced by the steering-assist of sHUB, which improves safety.

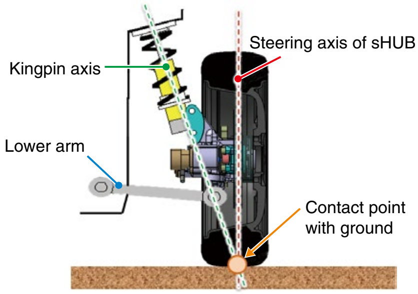

Fig. 4 Basic design of sHUB installed on front wheel

Fig. 5 shows an example of sHUB installed on the rear wheel. Similar to the case of the front wheels, it can be installed with modification only to the knuckle. In this case, the suspension system is a regular rigid axle (torsion beam). The rear wheel steering was easily achieved by merely installing sHUB on the torsion beam where the hub bearing is normally installed.

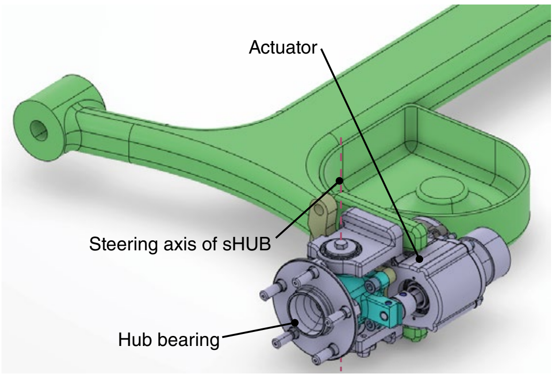

Fig. 5 sHUB installed on rear wheel

3. Configuration and Specification

3.1 Components

Fig. 6 shows the components of sHUB. sHUB is comprised of an actuator, hub bearing and knuckle. The function of the respective components is described as follows:

• Actuator
  Fixed to knuckle and steers hub bearing
• Hub bearing
  Rotary support of tire; rotary support of the steering axis of sHUB against the knuckle
• Knuckle
  Connection with vehicle suspension

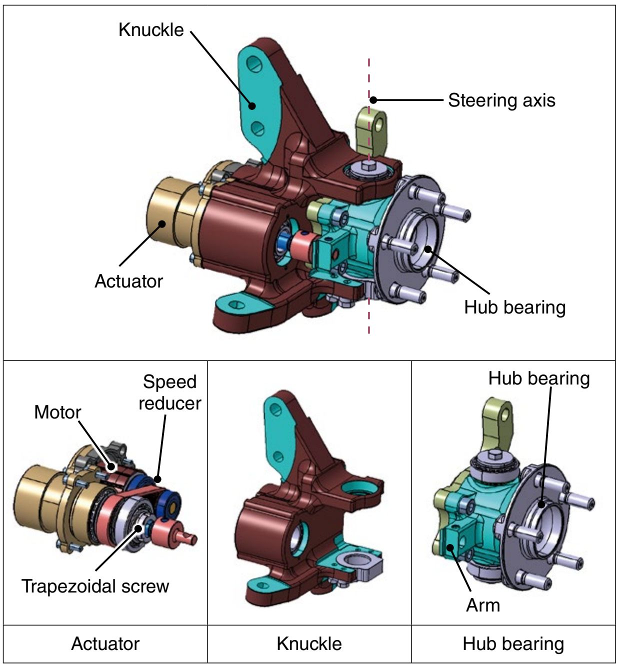

Fig. 6 Components of sHUB

The motor of the actuator is controlled by the controller based on an input, such as the vehicle speed and steering wheel angle in order to achieve the best tire angle. The rotation from the motor, through the reducer, is converted to linear motion by the trapezoidal screw, which drives the end of the arm installed on the hub bearing and steers the tire around the steering axis.

The reverse input from the tire due to the reaction force from the ground is blocked by the self-lock mechanism of the trapezoidal screw. Therefore, power consumption of the motor can be saved.

3.2 Specification

Table 1 shows the specification of the prototype, which was designed for front wheels of a C-segment vehicles with rear wheel drive. The weight of the prototype was 13.8 kg, which only adds 5 kg or less to the standard components (knuckle and hub bearing) of the original vehicle.

Table 1 Specification of prototype

Item	Values
Maximum steering torque	350 Nm
Supply voltage	24 V
Maximum steering angle	±3.5 deg
Maximum steering angular speed	16 deg/s
Weight	13.8 kg

4. Basic Performance Test

A C-segment rear-wheel drive vehicle was chosen as the test vehicle with the sHUBs described in Section 3.2 being installed on the front wheels.

4.1 Frequency Response Characteristics Test

A frequency response characteristics test was conducted in a stationary state by mounting the front wheels of the sHUB installed on the vehicle to a turntable. The actual angles were verified by giving an angle command in the form of a sinusoidal wave (0.5 deg. of amplitude and 1, 2, 4, 6 and 8 Hz of frequencies).

Fig. 7 shows the test results. The dashed curve indicates the command angle and the solid curve indicates the actual angle of sHUB. As the frequency increased, the delay of the actual angle against the command angle increased; however, the maximum frequency in practical use is 5 Hz or less and in this range the delay of the actual angle from the command angle was 0.025 sec or less, which is sufficiently small.

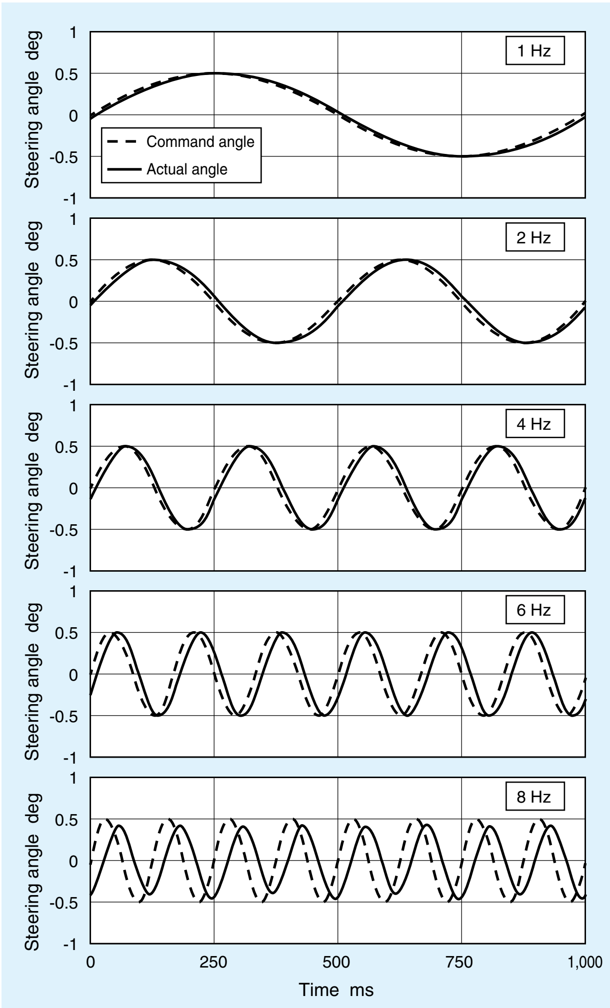

Fig. 7 Frequency response characteristics

4.2 Steering Response Speed Test

The steering response speed was obtained by steering the sHUB while a steering torque is applied to the hub bearing. The command value shown in **Fig. 8** (dashed line) was given to the controller to determine the steering response speed of sHUB. The steering response speed was determined from the slope of the actual measurement (solid line).

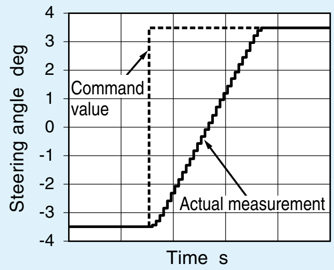

Fig. 8 Command value and measured value of steering angle

Fig. 9 shows the steering response speed of sHUB against the steering torque. As the steering torque increased, the steering response speed decreased. However, it satisfied the target response time of 10 deg/s or more in the entire range of the steering torque.

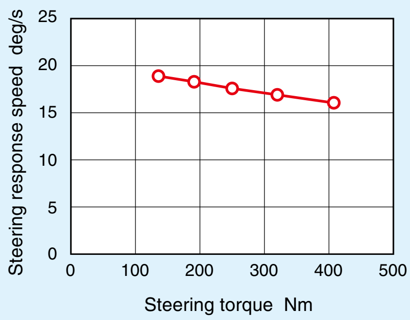

Fig. 9 Relationship between steering torque and steering response speed

4.3 Rigidity Test

The rigidity of the axle of a turning vehicle was verified against a moment load being applied to the tires. **Fig. 10** shows the flange angles of a standard hub bearing and sHUB for the same type of vehicle for comparison of moment rigidity.

As a result of the optimization of internal specification of the hub bearing, which is a component of sHUB, steering axis support bearing and bearing preload, the flange angle of sHUB increased 5% compared with standard hub bearings in the high-load range.

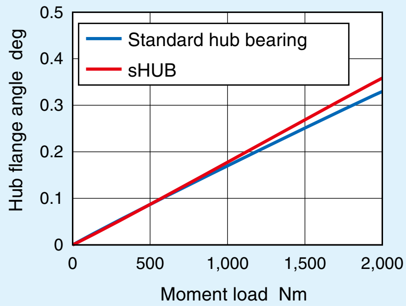

Fig. 10 Flange angle

5. Vehicle Motion Control by the Front Wheel Steering

A joint development with Yamakado/Kano Laboratory of Kanagawa Institute of Technology was conducted for verification of effective control method of sHUB.

"Control to Improve Transient Response" which improves the vehicle response in transient mode and "Control to Improve Turning Characteristics" which optimizes the lateral skidding angle of the tires in a steady turn of a vehicle were developed.

5.1 Control to Improve Transient Response[2), 3)]

This control adjusts time constants of 3 responses, namely, lateral skidding angle, yaw rate and lateral acceleration against the vehicle speed and steering by the correction of steering operation of sHUB for improvement of vehicle dynamic performance.

In order to verify the improvement of the vehicle responsiveness by this control law, a "pulse steering input" test was conducted using a test vehicle with sHUB according to the "Transient Response Test Procedures for Passenger Cars (JASO Z110:2003)."[4)] A test condition of 80 km/h vehicle speed and a triangular wave with pulse width of 0.5 s for drivers steering operation was used.

The results of frequency response of yaw rate and lateral acceleration against the steering wheel angle are shown in **Fig. 11**.

By using this control, it revealed that the vehicle responsiveness against steering operation improved, as the peak value increased and the phase lag improved, both for yaw rate and lateral acceleration in the frequency range (0.5 to 2.0 Hz) of the steering wheel angle, which is equivalent to normal driving.

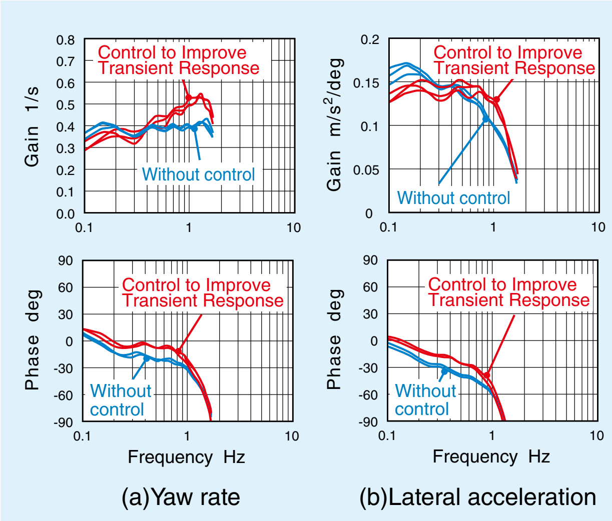

Fig. 11 Test result of frequency response characteristics

Next, the change of vehicle behavior was evaluated with the actual vehicle, with and without this control, by conducting a single lane change at the speed of 80 km/h on an asphalt course shown in **Fig. 12. Fig. 13** shows the change of yaw rate and lateral acceleration in the test. It revealed that this control decreases the required steering wheel operation and improves the response of yaw rate and lateral acceleration.

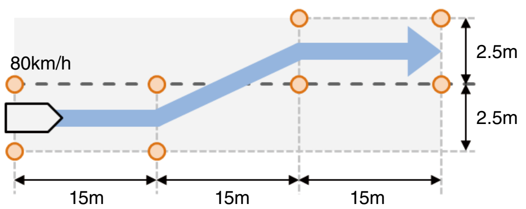

Fig. 12 Actual driving test course (single lane change)

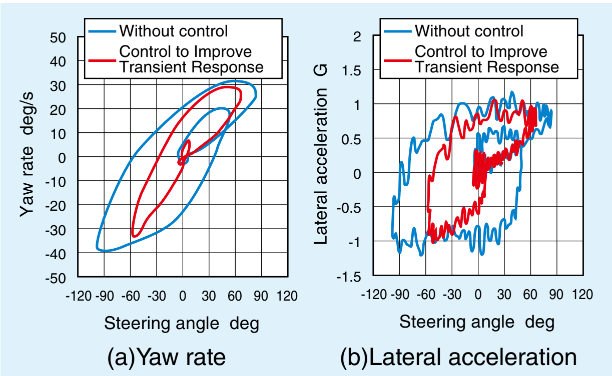

Fig. 13 Test result (yaw rate and lateral acceleration)

5.2 Control to Improve Turning Characteristics (SAHS)[5)]

The following shows the control law to efficiently utilize the maximum tire performance in response to the load shift during turns, in the entire speed range from ultra-low speed to mid/high speed when the load shift on the left and right wheels increases. This control law is called SAHS (Super Ackermann Hub Steer).

When a running vehicle makes a turn, load shift between the left and right wheels and lateral skidding occur. When the load on the inner wheel and outer wheel during a turn are represented by W_i and W_o respectively, and the lateral skid angle by β_n, (inner wheel: β_i, outer wheel: β_o), then the relationship between the cornering force and lateral skid angle is similar against the change of the load, which can be depicted as **Fig. 14**.

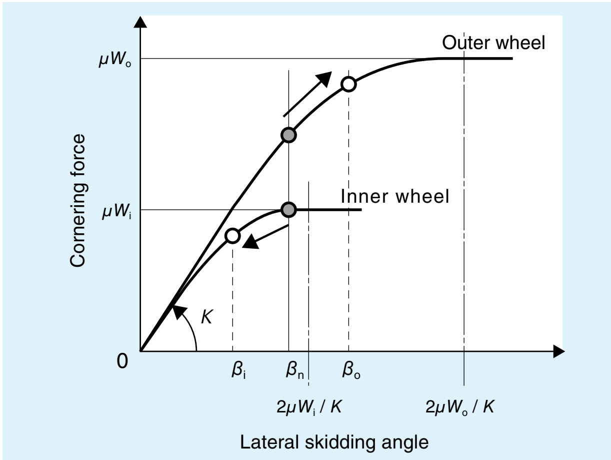

Fig. 14 Relationship between lateral skidding angle and cornering force

In SAHS control, the lateral skidding angle of the inner wheel is decreased and that of the outer wheel is increased by sHUB so that the loads on the right wheel and left wheel become equal($\beta_i/W_i = \beta_o/W_o$)(to the direction of the arrows in **Fig. 14**). With this control, the sum of the cornering forces can be increased without changing the average steering angles of the left and right wheels, utilizing both tires effectively during turns. In other words, at ultra-low speed where lateral acceleration (load shift) can be ignored, the control realizes an ideal Ackermann geometry and at mid/high-speed where lateral acceleration increases, reverse Ackermann geometry is followed.

An evaluation test was conducted for verifying the effect of SAHS using a test vehicle with sHUB. **Fig. 15** shows the layout of the test course. The change of vehicle behavior was evaluated with and without this control by inputting a steering maneuver ramping up to 130 degrees at 0.5 sec intervals starting from point A after straight running at a speed of 50 km/h. The control parameters were determined based on the sensitivity evaluation during driving.

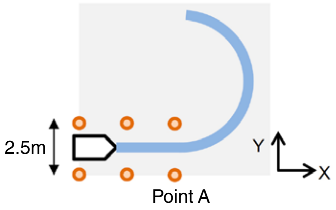

Fig. 15 J-turn test course layout

Fig. 16 shows the result of test. Without the control, the ratio of skidding angle against tire load (burden on the tire) is significantly different between the inner and outer wheels. On the other hand, with the control the load is equivalent between the inner and outer wheels. Therefore, the force from both tires is efficiently transmitted on the road surface. As a result, the turning radius decreased as shown in **Fig. 17**.

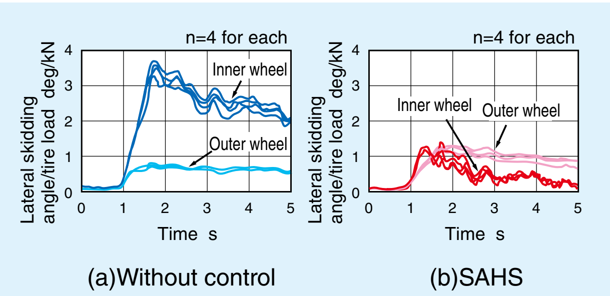

Fig. 16 Test result (load on tires)

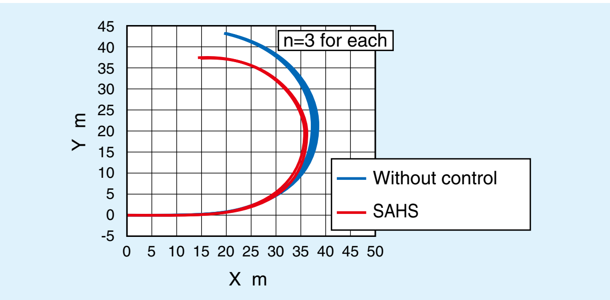

Fig. 17 Test result (driving trajectory)

6. Conclusion

Structure, specification and basic performance of the "Hub Bearing with Steering Assist Function (sHUB®)" were introduced.

Also, it was confirmed that two control methods (Control to Improve Transient Response and Control to Improve Turning Characteristics (SAHS)) can significantly improve the vehicle characteristics by applying correction to the steering angles of the left and right wheels against the driver's steering operation for improved vehicle dynamic performance, as shown in the driving test with sHUB installed on an actual C-segment vehicle. In addition, we are currently working on building an integrated control combining these two control methods.

Moving forward, we will study control methods to take advantage of sHUB more effectively for its application on many vehicles including being applied for the driving wheels. We believe in the high potential of sHUB for increasing the driving degrees of freedom in the "steering by wire" system which is expected to be a technology of the future in order to increase responsiveness even more, as it can apply corrective control at the closest position from the contact point between the tire and the ground.

References

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