1. Introduction

As environmental regulations are strengthened globally, each country has established stringent regulations for automobiles toward reduction of CO₂ emissions. Along with this trend, the electrification of automobiles has been accelerating with the active development of hybrid vehicles including plug-in, battery powered electric vehicles and fuel cell vehicles. Fig. 1 shows the production forecast of passenger vehicles globally. 48V mild hybrid vehicles (hereafter, 48V MHEV) are expected to grow to 25% of all the production vehicles by 2025 since electrical handling is easy and the implementation costs are low. It is known however, that the rate of improvement of fuel efficiency is about 15% maximum even if the effect to fuel cost against implementation costs are large. The implementation rate of these vehicles in terms of low fuel consumption such as electric vehicles and plug-in hybrid vehicles is expected to be slow due to the promulgation of infrastructure, battery supply and cost issues. Improvement of fuel efficiency of 48V MHEVs, which are expected to grow faster, is required to address the strengthening regulatory requirements on fuel efficiency in the near term.

![Fig. 1 Production forecast of global passenger vehicles (Our own analysis and forecast based on IHS Markit)](image)

Therefore, NTN has developed a Hub Bearing with Motor Generator Function (hereafter, eHUB), to be installed on the rear wheels (driven wheels) of front wheel-driven 48V MHEVs[1]. The following shows the development concept of eHUB.

1) Improved fuel efficiency of 48V MHEV vehicles
2) Improved vehicle dynamic performance
3) Installable on existing suspension systems

In the previous article, we reported that the eHUB improved fuel efficiency by 3.2% in WLTC mode when installed on the rear wheels of a front wheel-driven internal combustion engine vehicle (ICE vehicle)[1]. Additionally, eHUB can drive the left and right wheels independently with good responsiveness as it transmits torque directly to the wheel, and controls regenerative torque. These characteristics contribute to driving stability and ride comfort. In this article, improvement of vehicle dynamic performance based on the independent control of eHUBs on the left and right wheels is discussed, focusing on concept (2) above.

2. Basic Configuration

2.1 Structure and Specification

We set the following goal for the size of the outer diameter so that it can be installed on an existing suspension system.

- Outer diameter less than the inner diameter of brake disk
- Same axial length as a conventional hub bearing

A three-phase brushless DC motor was adopted to obtain as much output as possible in a limited amount of space. Table 1 shows the specification of the eHUB used for evaluations. The prototype eHUB was larger than the target size (width) requiring modification to the test vehicle. NTN is currently working on size modifications to the design achieving the same output and results.
### Table 1 Specification of eHUB

<table>
<thead>
<tr>
<th>Item</th>
<th>Target value</th>
<th>Prototype</th>
</tr>
</thead>
<tbody>
<tr>
<td>Appearance</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Outer diameter mm</td>
<td>φ 160</td>
<td>φ 159</td>
</tr>
<tr>
<td>Width mm (Hub bolts not included)</td>
<td>80</td>
<td>126</td>
</tr>
<tr>
<td>Weight kg</td>
<td>10</td>
<td>14</td>
</tr>
<tr>
<td>Driving voltage V</td>
<td>48</td>
<td>48</td>
</tr>
<tr>
<td>Maximum output kW</td>
<td>5.0</td>
<td>4.5</td>
</tr>
<tr>
<td>Maximum torque Nm</td>
<td>60.0</td>
<td>59.2</td>
</tr>
<tr>
<td>Maximum rotational speed min⁻¹ (Equivalent vehicle speed km/h)</td>
<td>1,700 (200)</td>
<td>1,200 (130)</td>
</tr>
</tbody>
</table>

### 2.2 Test Vehicle

Improvement of vehicle dynamic performance was reviewed by installing the eHUB on the front wheel-driven application of a B segment vehicle. The vehicle used for measuring fuel efficiency in the previous report was used for this test. The power train configuration is shown in Fig. 2 and the vehicle specification is shown in Table 2. A commercially available internal combustion engine vehicle (ICE vehicle) was modified to install the eHUB on the rear wheels. As shown in Fig. 3, the torsion beam was modified to install the eHUB and existing hydraulic brakes. The controller unit and battery were installed in the rear seating area and cargo space (Fig. 4). The eHUB was built as a control system independent from the existing vehicle system, that obtains information such as steering angle, acceleration and speed from the vehicle. Commercially available products were used for the 48V battery and controller unit, building an environment where the control model created for simulation can be directly evaluated with the actual vehicle.

### Table 2 Test vehicle specification

<table>
<thead>
<tr>
<th>Item</th>
<th>Specification</th>
<th>Remark</th>
</tr>
</thead>
<tbody>
<tr>
<td>Driving method</td>
<td>Front</td>
<td>wheel-driven</td>
</tr>
<tr>
<td>Main drive power</td>
<td>ICE</td>
<td></td>
</tr>
<tr>
<td>Transmission type</td>
<td>MT</td>
<td></td>
</tr>
<tr>
<td>Number of passengers</td>
<td>2</td>
<td>Rear seats were removed</td>
</tr>
<tr>
<td>Tire size</td>
<td>195/45/R17</td>
<td></td>
</tr>
<tr>
<td>Vehicle weight kg</td>
<td>1,207</td>
<td>No load</td>
</tr>
<tr>
<td>ABS system</td>
<td>OFF</td>
<td></td>
</tr>
<tr>
<td>Electronic stability control system</td>
<td>OFF</td>
<td></td>
</tr>
<tr>
<td>eHUB</td>
<td>Prototype</td>
<td>Refer to Table 1</td>
</tr>
<tr>
<td>eHUB installation</td>
<td>Rear wheels (left and right)</td>
<td>Torsion beam is modified</td>
</tr>
</tbody>
</table>
3. Direct Yaw Moment Control (DYC)

We worked on vehicle dynamic control taking advantage of the benefits of eHUB, which can drive the left and right wheels independently and regenerate energy. Vehicle dynamic performance can be improved by appropriately operating eHUB depending on the vehicle information such as the speed, steering angles and changing the vehicle behavior.

The approach to actively producing different driving inputs to the left and right wheels to directly control the vehicle yaw moment is called Direct Yaw Moment Control (hereafter, DYC)\textsuperscript{2,3}. DYC is expected to improve the responsiveness of yaw rate against steering and vehicle maneuverability on slippery road surfaces such as roads with compacted snow or ice.

An approach to produce yaw moment from the difference of driving inputs to the left and right wheels to compensate for the difference between the target yaw rate and vehicle yaw rate is known as the DYC yaw rate response. The target yaw rate $\tau_t$ is expressed by Equation (1) in conventional DYC.

$$\tau_t(s) = G_D^e(0) \frac{1 + \tau_r s}{1 + 2\beta s + \frac{1}{(a\omega)^2}s^2}\delta(s)$$

Where,

- $\tau_t$ : target yaw rate [rad/s]
- $\delta$ : natural frequency of yaw rate response
- $\zeta$ : damping ratio of yaw rate response
- $\tau_r$ : time constant of yaw rate response [s]
- $G_D^e(0)$ : steady gain of yaw rate response
- $\alpha$ : control parameter of natural frequency
- $\beta$ : control parameter of damping ratio

Equation (1) shows that the natural frequency and damping ratio of the yaw rate response to steering can be changed by arbitrarily setting the control parameters $\alpha$ and $\beta$. The yaw moment $M_r$ necessary to achieve this yaw rate is expressed by Equation (2).

$$M_r(s) = G_D^e(0) \frac{1 + \tau_r s}{1 + 2\beta s + \frac{1}{(a\omega)^2}s^2} \left( 1 + \frac{2\tau_r s}{(a\omega)^2} \right) \delta(s) - G_D^e(0) \frac{1 + \tau_r s}{1 + 2\beta s + \frac{1}{(a\omega)^2}s^2} \delta(s)$$

Where,

- $T_m$ : time constant of yaw moment response [s]
- $G_D^e(0)$ : steady gain of yaw moment response
- $M_r$ : required yaw moment [Nm]

Equation (2) shows that the yaw moment is determined depending on the steering angular velocity and angular acceleration in the conventional DYC. By adjusting $\alpha$ and $\beta$ to maximize the effect of DYC, the yaw moment becomes large due to the term that depends on the steering angular velocity, resulting in the required maximum torque of several hundreds of Nm per wheel, on both wheels. Therefore, the conventional DYC cannot be applied to eHUB, which has the maximum torque of a magnitude of tens Nm.

Therefore, we focused on the stability of maneuverability on slippery roads and adjusted the control parameters for improving the yaw rate response at the beginning of steering operation. If we set $\beta = \alpha$ in Equation (1), the target yaw rate can be expressed by Equation (3) and the required yaw moment by Equation (4), respectively, improving the torque response against the steering angular acceleration.

This enables improved response to the initial steering operation even with relatively low torque.

$$\tau_t(s) = G_D^e(0) \frac{1 + \tau_r s}{1 + 2\alpha s + \frac{1}{(a\omega)^2}s^2}\delta(s)$$

$$M_r(s) = G_D^e(0) \frac{1 + \tau_r s}{1 + 2\alpha s + \frac{1}{(a\omega)^2}s^2} \left( 1 + \frac{2\tau_r s}{(a\omega)^2} \right) \delta(s) - G_D^e(0) \frac{1 + \tau_r s}{1 + 2\alpha s + \frac{1}{(a\omega)^2}s^2} \delta(s)$$

The yaw motion of the initial steering operation is enhanced when $\alpha > 1$, and suppressed when $\alpha < 1$. Torque of the eHUB to achieve the yaw moment of Equation (4) is Equation (5).

$$T_L = -\frac{R}{D}M_r, \quad T_R = +\frac{R}{D}M_r$$

Where,

- $D$ : rear wheel tread [m]
- $R$ : dynamic effective radius of tire [m]
- $T_L, T_R$ : torque of eHUB (left and right) [Nm]

Fig. 5 shows the result of the simulation for the required torque against the steering angles. In the ordinary DYC, the torque is determined according to the change of steering angular velocity and steering.
angular acceleration. In contrast, in the DYC for the eHUB, since the torque responds to the change of steering angular acceleration, the increase in torque is faster compared with ordinary DYC. A driving test of a single lane change on a low $\mu$ road was conducted using this method for setting parameters. As shown in Fig. 6, the vehicle’s speed is adjusted to 30 km/h in the speed adjustment zone and the acceleration pedal is released at a predetermined point to coast for a lane change. Fig. 7 shows the driving trajectory of the vehicle. The figure shows an average of 3 runs under the same conditions. Without control and with DYC ($\alpha = 0.8$), the vehicle turned wide when steering back (at around 20 - 30 m in the figure), but the vehicle with DYC ($\alpha = 1.2$) turned smoothly and remained stable. Fig. 8 shows the change of yaw rate against the steering angle. Applying DYC ($\alpha = 1.2$) improved traceability of yaw rate to steering angle and the amount of steering significantly reduced compared to the vehicle without control. That means that the vehicle behavior responds well to the steering operation and the vehicle turns more easily. On the other hand, in the case of DYC ($\alpha =0.8$), the amount of steering is almost the same as the case without control but the area inside the curve is larger. That means that the yaw rate response is delayed against the steering operation, the vehicle behavior does not respond well and the vehicle turns less easily. As such, we could verify that even a small amount of torque, such as the eHUB, can change the vehicle behavior by driving/regenerating the left and right wheels separately.

4. Longitudinal Acceleration Control According To Lateral Acceleration

DYC in the previous Chapter is effective when the friction coefficient between the tire and the road surface is low. However, these driving conditions are limited so another method for controlling vehicles more cohesively with longitudinal and lateral acceleration is being proposed by adding longitudinal acceleration according to lateral acceleration.

Fig. 9 shows a graphical representation of longitudinal and lateral acceleration during turns of everyday drivers and expert drivers in regular driving conditions. Ordinary drivers tend to decelerate before a turn and only maneuver the steering wheel while turning. Therefore, the lateral acceleration abruptly changes after deceleration as shown in (a) in the figure. The passengers feel significant change of inertial force that may cause carsickness or discomfort. On the other hand, expert drivers adjust acceleration/deceleration along with steering operation, which makes the combined acceleration of longitudinal and lateral acceleration transition along with a smooth curve. Therefore, the passengers feel a smoother change of inertial force and an improved comfort level.

The driving technique of expert drivers can be achieved by adding longitudinal acceleration to lateral acceleration, which can be expressed in Equation (6). The left and right torque from the eHUBs are the same to realize this and can be expressed in Equation (7).
Fig. 9 Lateral/longitudinal acceleration during a turn (graphical representation)

\[ G_x = -\text{sgn}(G_y \cdot \dot{G}_y) \frac{a_x}{1 + T_x x_p} |\dot{v}_y| \]  \hspace{1cm} (6)

\[ T_L = T_R = \frac{1}{2} R m c_x \]  \hspace{1cm} (7)

Where,
- \( G_y \): vehicle lateral acceleration [m/s²]
- \( \dot{G}_y \): vehicle lateral jerk (time derivative of \( G_y \)) [m/s³]
- \( G_x \): vehicle target longitudinal acceleration [m/s²]
- \( T_x \): first-order lag time constant [s]
- \( m \): vehicle weight [kg]
- \( a_x \): control parameter of longitudinal acceleration

Fig. 10 shows the graphic representing longitudinal acceleration control. The longitudinal acceleration is controlled with the torque produced by eHUB according to lateral acceleration. Deceleration is added when the vehicle enters into a curve so that the load moves from the rear wheels to the front wheels and the yaw moment to assist turning is created. On the other hand, acceleration is added when the vehicle exits from the curve so that the load moves from the front wheels to the rear wheels and the yaw moment to restore the vehicle stability is created.

Fig. 11 shows the result of the driving test with an actual vehicle similar to that in Chapter 3 to verify the effect of the longitudinal acceleration control through drive/regenerating brake control of the eHUB. Two control conditions were used: without control and longitudinal acceleration control. The results show an average of 3 runs, similar to the test with DYC. The longitudinal/lateral acceleration transitioned in a smooth curve when longitudinal acceleration control was applied.

These results suggest high potential for improvement of vehicle dynamic performance if appropriate vehicle operation is implemented, even with a motor/generator of small output such as eHUB. In the next stage, we will build an integrated control combining DYC, longitudinal acceleration control and optimum logic for fuel efficiency, etc.
5. Conclusion

In this paper, the effect of vehicle dynamic control was verified with the eHUB, which improves fuel efficiency and driving performance of 48V MHEVs without significant modification to the vehicles, and the following result was obtained.

(1) Direct Yaw Moment Control
It was verified that DYC with higher sensitivity to the steering angular acceleration was effective for the stability of driving trajectory and the reduction of the amount of steering in a single lane change on a low µ road.

(2) Longitudinal Acceleration Control Coupled with Lateral Acceleration
It was verified that application of longitudinal acceleration, which is said to contribute to the improvement of ride comfort, was effective for the smoother change of lateral/longitudinal combined acceleration and the improvement of ride comfort in steering.

In the next phase, we will work on improvement of the eHUB for higher output and higher efficiency to enhance the effect of reduced fuel consumption, as well as the improvement of vehicle dynamic performance for practical applications.

References