Brief Report

Energy Analysis of In-wheel Motor Vehicle with Active Ride Control

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1. Introduction

Recently, the electrification of automotive powertrain systems has been promoted as a means of helping to prevent global warming, and the development of electric vehicles (EVs) has become a global trend. Since EVs equipped with in-wheel motors do not require drive shafts, the driving torque has a rapid response and can be controlled independently. By utilizing in-wheel motors, an active ride control method has been proposed to damp the motion of the sprung mass.(1-3)

However, since one of the difficult issues in developing electric vehicles is improving the mileage per charge, it is necessary to understand the effect of vehicle dynamics control on energy performance. Therefore, it was decided to construct a vehicle dynamics simulation containing a motor model capable of considering the electromagnetic characteristics to predict the power consumption accurately.

The purpose of this paper is to describe the construction of a vehicle-motor integrated model. Finally, based on the simulation results, this paper discusses the relationship between the motion of the sprung mass and the power consumption.

2. Method

2. 1 Vehicle-motor Integrated Model

Figure 1 shows the vehicle-motor integrated model constructed in this paper. The vehicle model consists of a sprung body with six degrees of freedom and four unsprung bodies with three degrees of freedom for longitudinal, vertical, and rotational motion. The Magic Formula combined model is applied to the tire model. Although the driving force acts as a longitudinal force on the sprung mass, it generates a vertical reaction force through the suspension. Since the vertical force is large due to the in-wheel motor mechanism, it is possible to use the force for the sprung body as the damping force. Among the sprung motions, it is impossible to control pitching and heaving simultaneously for the constraint of the longitudinal force. Therefore, this paper targets pitch and heave control, which have a close mutual relationship.

The control torque is calculated to generate a vertical damping force proportional to the velocity of the sprung mass on the basis of skyhook theory. Each control gain is set to the same multiple based on each original damping ratio to equalize the damping effect between pitch and heave control. The motor model consists of an interior permanent magnet synchronous motor model, an efficiency optimization algorithm block, and a current controller. Equivalent circuit theory(4) was adopted to develop the motor model. The parameters were obtained in bench tests. The

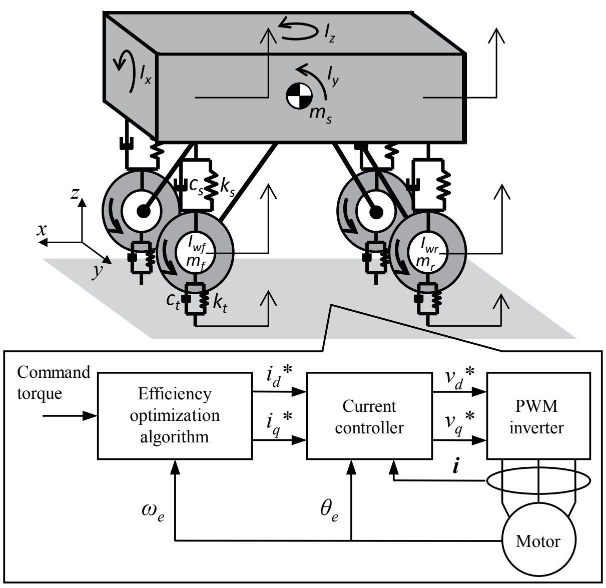

Fig. 1 Vehicle-motor integrated model.

reduction gear loss in the motor unit was also modeled as the transmission efficiency calculated from the gear mesh loss.

2. 2 Test Vehicle Equipped with In-wheel Motors

A passenger vehicle was customized to form the test vehicle. The drive line was removed, and in-wheel motors were installed at each wheel. The major specifications are shown in **Table 1**.

3. Results

3. 1 Power Consumption Characteristics

Figure 2(A) compares the simulation and experimental results for the motor power during pitch control at 60 km/h on a rough road. The simulation results exhibit the same trend as the experiment results. Figure 2(B) shows the increase rate of power consumption compared to that without control. With respect to the pitch control, the rate decreases as the vehicle speed increases. With respect to the heave control, the rate decreases at lower and higher speeds.

Table 1 Specifications of the test vehicle.

Vehicle mass	2100 kg
Max. power	40 kW × 4
Max. torque at axle	550 Nm × 4
Max. vehicle speed	200 km/h

(A)
(B)

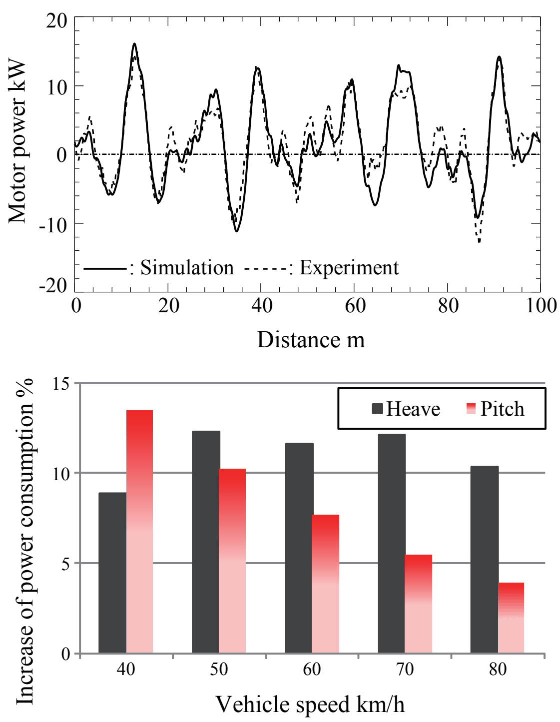

Fig. 2 Example of motor power response (A) and increase rate of power consumption for active ride control (B).

3. 2 Fundamental Study on Power Consumption

Assuming that the motor efficiency is constant at any operating point, the increase in instant power consumption ΔP can be formulated as follows:

$$\Delta P = \frac{(1-\eta^2)}{\eta}(T_C - T_0)\,\omega, \quad (1)$$

where T_C is the control torque, T_0 is the wheel torque, ω is the wheel angular velocity, and η is the motor efficiency. The above equation indicates that less control torque and higher motor efficiency is desirable for lower power consumption.

The motor control torque affects the power consumption. **Figure 3**(A) shows the effect of wheelbase filtering[(5)] on the heave and pitch input around the sprung natural frequency. Unlike for heave, the pitch input decreases with the vehicle speed. Therefore, the vehicle controller requires less control torque.

On the other hand, the motor efficiency also affects the power consumption. As shown in Fig. 3(B),

(A)
(B)

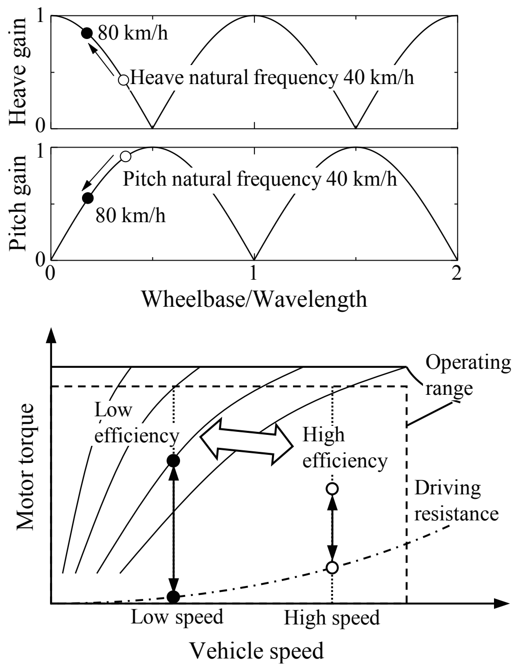

Fig. 3 Wheelbase filtering (A) and operating point change under ride control (B).

especially in pitch control, the motor efficiency improves as the motor speed increases corresponding to the vehicle speed. Therefore, the more efficient operating point contributes significantly to less power consumption coupled with a decrease in control torque during ride control. Since the control torque must be applied under the constraints of vehicle speed, the active ride control has an efficient speed zone.

4. Conclusion

A vehicle-motor integrated model was constructed by applying equivalent circuit theory to the development of the in-wheel motor model, and an actual vehicle test validated the appropriateness of the integrated model. Simulations also revealed the relationship between the power consumption and the sprung motion. Based on this knowledge, an efficient control method and optimum specifications of motors, drivelines, and suspensions will be studied in future works.

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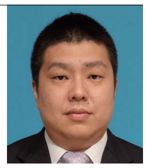

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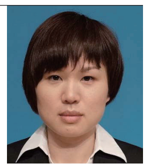

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