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ORIGINAL ARTICLE

Effect of Inner and Outer Wheels Driving Force Control on Small Electric Vehicle

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ABSTRACT – In this study, in order to improve steering stability during turning, we devised an inner and outer wheel driving force control system that is based on the steering angle and steering angular velocity, and verified its effectiveness via running tests. In the driving force control system based on steering angle, the inner wheel driving force is weakened in proportion to the steering angle during a turn, and the difference in driving force is applied to the inner and outer wheels by strengthening the outer wheel driving force. In the driving force control (based on steering angular velocity), the value obtained by multiplying the driving force constant and the steering angular velocity, that differentiates the driver steering input during turning output as the driving force of the inner and outer wheels. By controlling the driving force of the inner and outer wheels, it reduces the maximum steering angle by 40 deg and it became possible to improve the cornering marginal performance and improve the steering stability at the J-turn. In the pylon slalom it reduces the maximum steering angle by 45 deg and it became possible to improve the responsiveness of the vehicle. Control by steering angle is effective during steady turning, while control by steering angular velocity is effective during sharp turning. The inner and outer wheel driving force control are expected to further improve steering stability.

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Motion control; Driving stability; Automobile; Vehicle dynamics; Driving support; Maneuverability

INTRODUCTION

In recent years, the tendency to assist steering stability by electronic control is rapidly spreading in the automobile industry. Technologies for direct yaw moment control aimed at minimising vehicle body yaw motions have been actively developed as techniques for improving steering stability, and control improvements for the driving force of the inner and outer wheels are one of the areas of particular interest [1, 2]. In addition, research on vehicle attitude control by driving force distribution is also being conducted in conventional internal combustion engine vehicles. Still, it is thought that EV that drive the driving wheels independently can achieve more accurate driving force distribution. Steering systems that include derivative terms have been reported to increase yaw rate and lateral acceleration responses in the normal driving area. However, the effect can be obtained in the low lateral acceleration region where the cornering force of the front wheels is secured, but the desired effect cannot be obtained in the region where the lateral acceleration is large because the cornering force of the front wheels becomes saturated.

On the other hand, in the drift region, it has been clarified that the delay of counter-steer during drift cornering can be improved by differential steering assist [3]. Further, by performing derivative steering assistance control according to the driving situation, it has been reported that it is possible to perform the steering system control with no discomfort to the driver [4-6]. In driving force control, a couple of forces are generated around the centre-of-gravity (COG) point by applying independent driving forces to the inner and outer turning tires of a vehicle being directed by the steering wheel steering angle in order to control the yaw moment [7-11]. The steering characteristics of automobiles change from moment to moment due to the acceleration and deceleration of the vehicle [12,13]. In particular, when an automobile exhibits oversteer characteristics due to excessive deceleration, it can easily enter an unstable state, which is dangerous because it is difficult for an average driver to keep the vehicle from spinning out of control [14]. However, it is possible to control the yaw moment by manipulating the driving control force of the inner and outer wheels of a turning vehicle. So far, various developments have been made for driving force control, including driving force distribution and AWD [15]. As one of them, direct yaw moment control (DYC), which directly controls the yaw moment of a vehicle, has been proposed and put into practical use. This has made it possible to reduce behavioural changes during acceleration and deceleration near the limit of turning lateral acceleration. Since this method directly controls the yaw moment of the vehicle by using the difference in braking force and driving force of the tire, the desired yaw moment is generated as long as the tire has a front-rear force generation margin regardless of acceleration and deceleration or turning state. It can be expected to improve manoeuvrability and stability even in the limit area.

A Honda Legend automobile developed by Honda R&D Laboratories that is equipped with a four-wheel-drive system called Super Handling-All Wheel Drive (SH-AWD) is already on the market [16, 17]. By freely changing the driving force of the four wheels according to the driving conditions, even people who are unfamiliar with driving can drive with

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a full performance of the tires of the car, and improvement in driving stability can be expected. Nevertheless, since there have been few studies that discuss yaw moment control in relation to steering wheel angle, this study aims to improve marginal vehicle cornering performance by using steering wheel operations to assist the driving force.

EXPERIMENTAL APPARATUS

Small Electric Vehicle

We fabricated and used a small electric vehicle consisting of one mainframe and front and rear wheel suspension units. In our experiments, the tire tread was widened to produce a low COG because of the need to facilitate pylon slalom running and J-turns. The underbody of the unit was equipped with identical camber control mechanisms for the front and rear wheels. The car body frame was designed with reference to the dimensions of general miniature vehicles. Figure 1 shows the computer-assisted design (CAD) image of our vehicle design, and Table 1 shows the vehicle specifications.

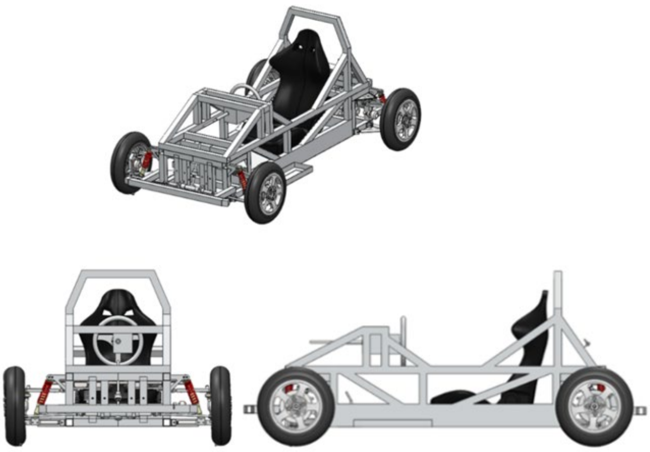


Figure 1. Small electric vehicle.

Table. 1. Specification of a small electric vehicle.

Item	Performance
Vehicle total weight (kg)	500
full length (mm)	2536
Full width (mm)	1480
Total height (mm)	1125
Wheel distance (mm)	2009
Tire (front wheel/rear wheel)	150/70-13
Motor rated output (kW)	3.0 × 2

Outline of Inner and Outer Wheels Driving Force Control

Inner and outer wheels driving force control system based on steering angle

The small electric experimental vehicle used in this study is equipped with driving motors mounted on both left and right rear wheels, and a microcomputer controls the accelerator opening degree ratios of these motors. Figure 2 shows the block diagram of inner and outer wheels driving force control system based on the steering angle. Figure 3 shows the configuration of the inner and outer wheel driving force control system. The steering angle is obtained from the rotary encoder mounted on the steering wheel, and the current accelerator opening degree is acquired from a potentiometer mounted on the accelerator pedal. The motor driver controls the motor according to the signal sent from the microcomputer. The steering angle is detected by the rotary encoder while the potentiometer detects the accelerator opening. The motor output varies by controlling the ratio of the accelerator opening degree using pulse width modulation (PWM) control. Steering angular velocity is calculated by differentiating the steering velocity in the logic. The initial steering position is automatically adjusted by steer-by-wire. When the steering angle is within the range of ±30, the vehicle is considered to be in a straight travel state, and normal driving force (without inner and outer ring control) was used. Figure 4 shows the flow chart of the inner and outer wheel drive force control. Equation (1) shows the driving force control of the inner and outer wheels, which is governed by the steering angle. In this equation, the driving force applied to the outer and inner rings is plus (+) and minus (–), respectively.

$$T_1 = T_0 \pm P_1 \cdot \delta_H \tag{1}$$

where T_1 is the actual driving force, T_0 is the initial driving force, P_1 is driving force constant, and δ_H is steering angle.

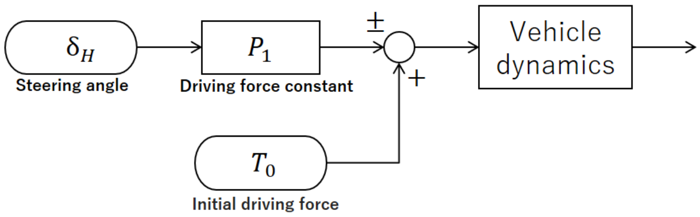


Figure 2. Block diagram of inner and outer wheels driving force control system based on the steering angle.

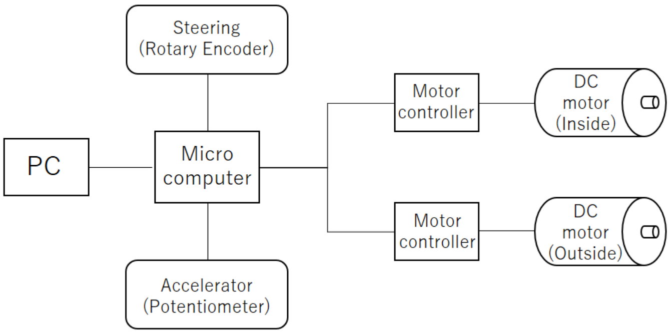


Figure 3. Inner and outer wheels driving force control system.

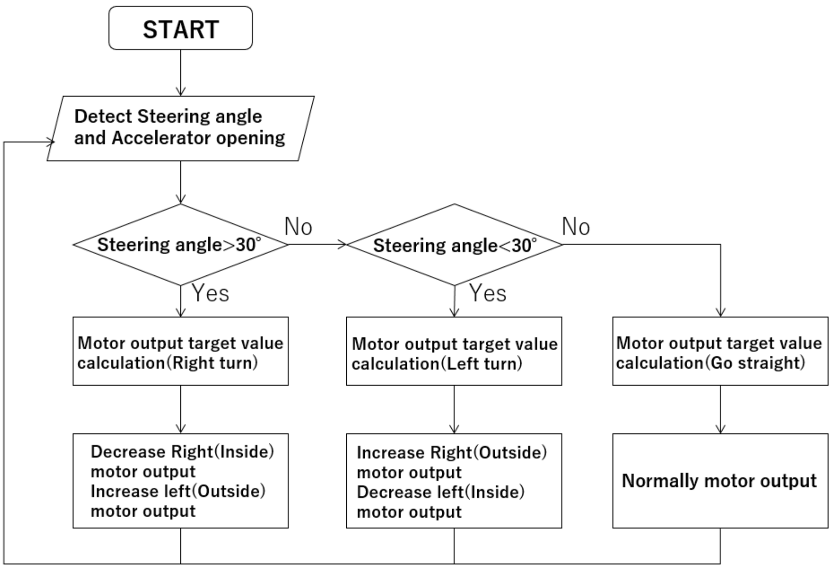


Figure 4. Flow chart of inner and outer wheels driving force control system.

Inner and outer wheels driving force control system based on steering angular velocity

Equation (2) shows the method of controlling the driving force of the inner and outer wheels based on the steering angular velocity. The actual driving force T_2 method produces the actual driving force by adding the inner and outer wheel initial driving force T_0 and the steering angular velocity $\dot{\delta_H}$ multiplied by the driver's driving force constant P_2. Steering angular velocity $\dot{\delta_H}$ is calculated as gain, and this equation is conceptual and not unit converted. By varying the value of P_2, the effectiveness of the inner and outer wheels driving force control based on the steering angular velocity can be modified. In that equation, the driving force applied to the outer ring and outer rings is plus (+) and minus (–), respectively. When this steering system is used in an emergency avoidance situation, the outer wheel driving force increases and the inner wheel driving force decreases in proportion to the steering angular velocity. This makes it possible to obtain a more efficient turning moment and improve the effectiveness of the rudder action. Furthermore, when the steering wheel stops moving, the driving force assist provided due to the steering angular velocity ceases, and the steady-state is stabilised. To prevent the value of P_2 from becoming too large, we set limits with a certain value above the program. In this experiment, the driving force of the inner and outer wheels that is based on the steering angular velocity is not the same as the driving force applied to the outer ring during a turn. Instead, the inner ring driving force is reduced by the steering angular velocity and the outer ring driving force is increased or decreased based on the accelerator opening degree. The driving force difference between the inner and outer rings is set to produce efficient turns. Figure 5 shows the block diagram of the inner and outer wheels driving force control system based on steering angular velocity.

$$T_2 = T_0 \pm P_2 \cdot \dot{\delta_H} \tag{2}$$

where T_2 is the actual driving force, T_0 is the initial driving force, P_2 is the driving force constant and $\dot{\delta_H}$ is the steering angular velocity.

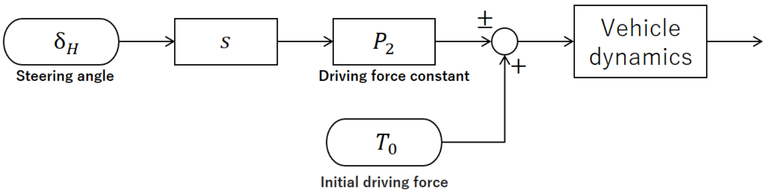


Figure 5. Block diagram of the inner and outer wheels driving force control system based on steering angular velocity.

Experiment Method

In this section, we examine the effectiveness of our proposed method in which driving force is applied to the inner and outer wheels according to the steering angle. The inner and outer wheel driving force control is based on the steering angular velocity. First, pylon slalom and J-turn tests were performed using normal steering. J-turn is a reversing vehicle by rotating 180 degrees and travelling manoeuvred facing forward without changing the travelling direction. In the pylon slalom course, the approach distance from the start position was 25 m, the distance from the first pylon to the last pylon was 45 m, and the distance between the pylons was 9 m. For the J-turn course, the approach distance was set to 60 m, and a half-circle with a radius of 7 m. The vehicle speed was 25 km/h. The pylon slalom course is shown in Figure 6 while the J-turn course is in Figure 7. Also, the experimental pattern is shown in Table 2. In the experimental results, a comparison was made for the yaw rate waveform phase (measured with the installed six-axis motion sensor), and waveform phase of the steering angle of the steering wheel.

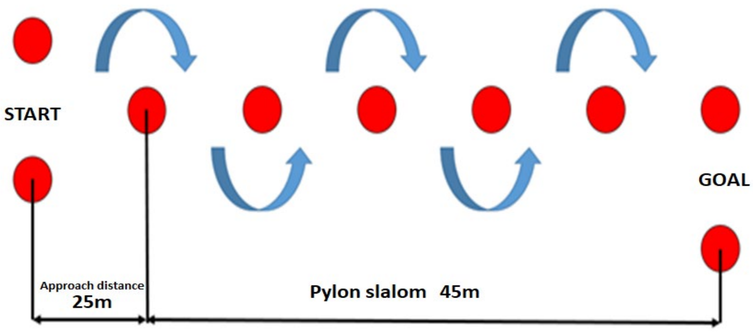


Figure 6. Pylon slalom course.

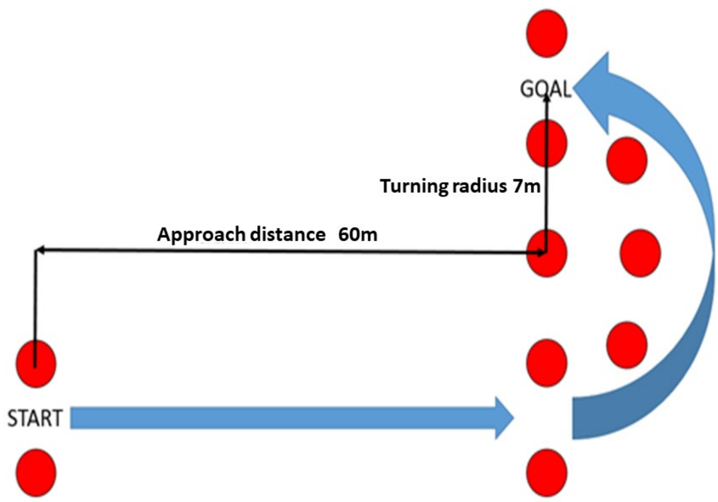


Figure 7. J-turn course.

Table. 2. Experimental pattern.

Assist pattern	Definition
Normal steering	Maximum inner and outer wheel driving force 100%
Inner and outer wheels driving force control system according to the steering angle	Inner wheel driving force minimum 30%: Outer ring driving force maximum 100%
Inner and outer wheels driving force control system according to the steering angular velocity	Inner wheel driving force minimum 30%: Outer ring driving force maximum 100%

EXPERIMENTAL RESULTS

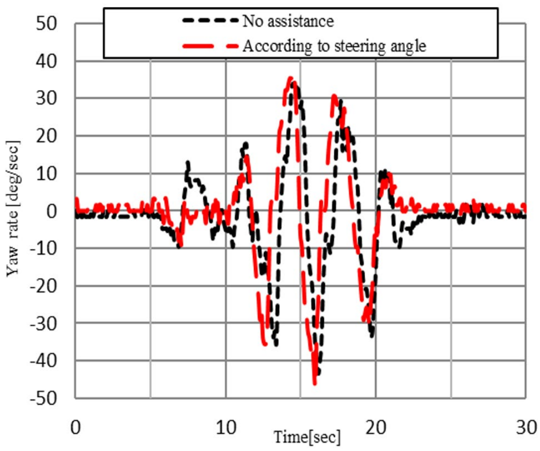
Inner and Outer Wheel Driving Force Control in Pylon Slalom Experiment

Table 3 shows the subject rating value of easiness of steering action to arrival pylon of goal (Pylon slalom). Subject evaluated the easiness of driving and the sense of stability based on the feeling and found that the difference was quite large. Figure 8 shows the yaw rate and steering angle of the steering angle proportional control and the pylon slalom experiment without control. When comparing the steering angle proportional control and yaw rate of the pylon slalom running results obtained without control, Figure 8(a) shows that the waveform phase is advanced. However, since the yaw rate increase is uncontrolled and no change is observed, we can confirm that additional driving force difference must be applied in order to efficiently navigate the slalom course. When comparing the steering angles, it was found that the steering angle proportional control tended to obtain improved turning characteristics because the steering angle proportional control decreased by 40 deg at the maximum compared with without control.

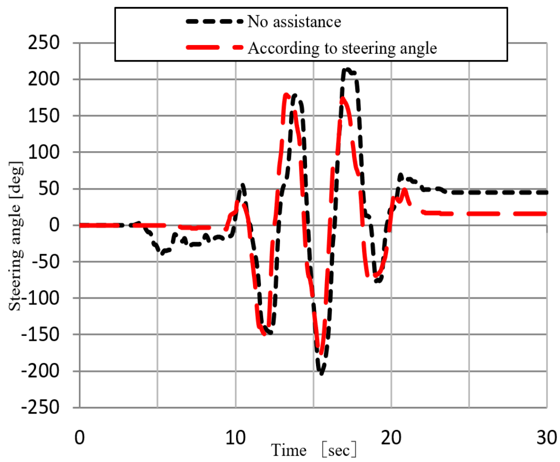
Table 3. Subject rating value of easiness of steering action to arrival pylon of goal.

	No assistance	According to the steering angle	According to steering angular velocity
Pylon slalom	2~3	3~4	4~5

**The following subject rating value was made:1,poor; 2,fair; 3,average; 4,good; 5,excellent.



(a)



(b)

Figure 8. Comparison between steering angle proportional control and no assistance during pylon slalom driving (a) yaw rate and (b) steering angle.

Figure 9 shows the yaw rate and steering angle of the steering angular velocity control and the pylon slalom experiment without control. Comparing the steering angular velocity control and the yaw rate of the pylon slalom running without control, Figure 9(a) shows that the waveform phase advances, with the maximum increased by as much as 20 deg/sec. Additionally, the gradient in the rise and convergence is steep. From these results, it can be said that the vehicle responsiveness has been improved by the steering angular velocity control. From the steering angles seen in Figure 9(b), it can be confirmed that when the steering angular velocity control is used, the steering angle decreases at all pylon passages by 45 deg at maximum. This indicates that the steering angular velocity control improved vehicle response and turning stability.

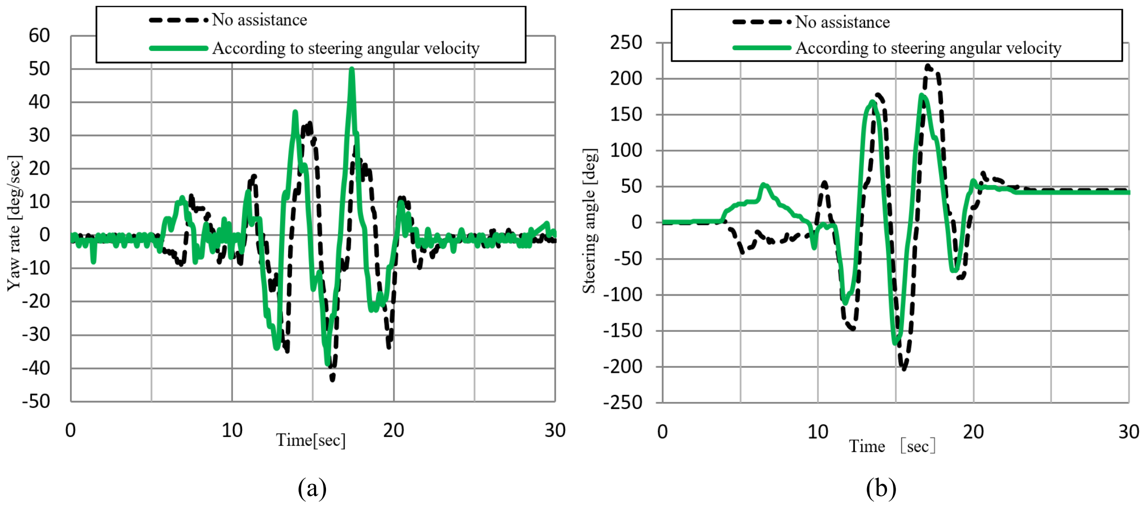


Figure 9. Comparison between Steering angular velocity control and no assistance during pylon slalom driving (a) yaw rate (b) steering angle.

Figure 10 shows the yaw rate steering angle, and the pylon slalom running test results when steering proportional angle control and steering angular velocity control applied. When comparing the yaw rate of pylon slalom travel with the steering angle speed control provided by the steering angle proportional control and steering angular velocity control, as seen in Figure 10(a) and 10(b), there are no major differences such as a waveform phase advancement. However, when compared with the steering angle proportional control, it confirms that the yaw rate increased by a maximum of 20 deg/sec and a maximum of 40 deg reduces the steering angle. In pylon slalom travel, the vehicle responsiveness was improved by the steering angle proportion and steering angular velocity inner and outer wheels driving force control, which also resulted in improved steering stability. Additionally, since numerous steering operations are required in the case of pylon slalom travel, the use of steering angular velocity control can advance the steering phase more than the steering proportional angle control. The steering angular velocity control is more effective than the steering proportional angle control in that situation.

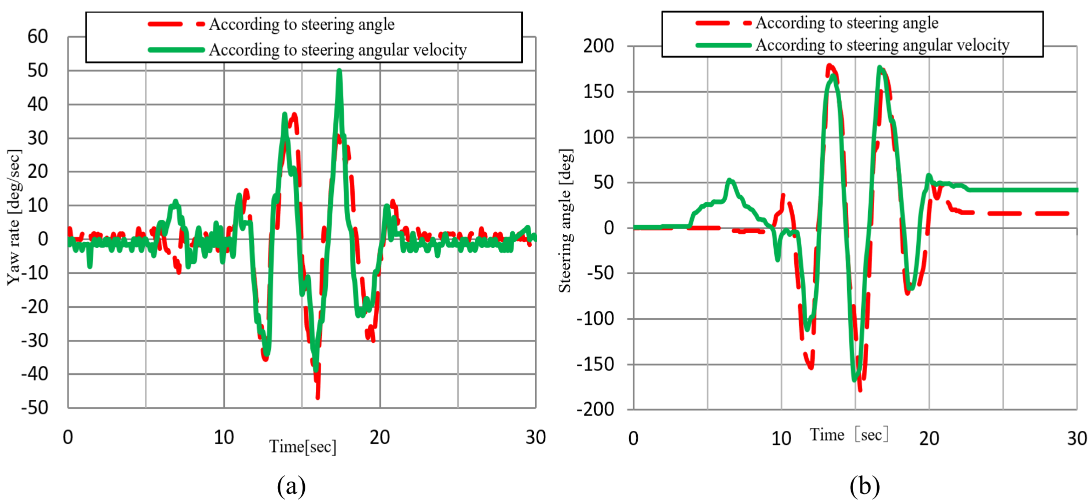


Figure 10. Comparison between steering angle proportional control and Steering angular velocity control during pylon slalom driving (a) yaw rate (b) steering angle.

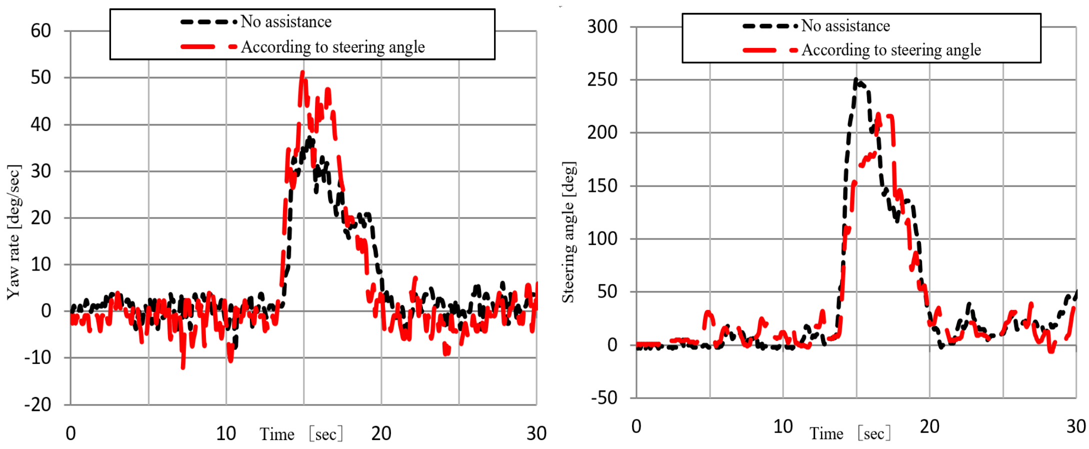
Inner and Outer Wheel Driving Force Control J-Turn Experiment

Table 4 shows the subject rating value of easiness of steering action to arrival pylon of goal (J-turn). Subject evaluated the easiness of driving and the sense of stability based on the feeling and found that the difference was quite large. Figure 11 shows the yaw rate and steering angular of the J-turn experiment without control and steering angle proportional control. Comparing the yaw rate of the J-turn test without control and the steering angle proportional control with the steering angle, it can be confirmed from Figures 11(a) and (b) that the rise in the initial stage of turning becomes faster and the convergence improves when steering angle proportional control is used. It can also be confirmed that the steering angle decreased by about a maximum of 40 deg.

Table 4. Subject rating value of easiness of steering action to arrival pylon of goal (J-turn).

	No assistance	According to steering angle	According to steering angular velocity
J-turn	1~2	4~5	3

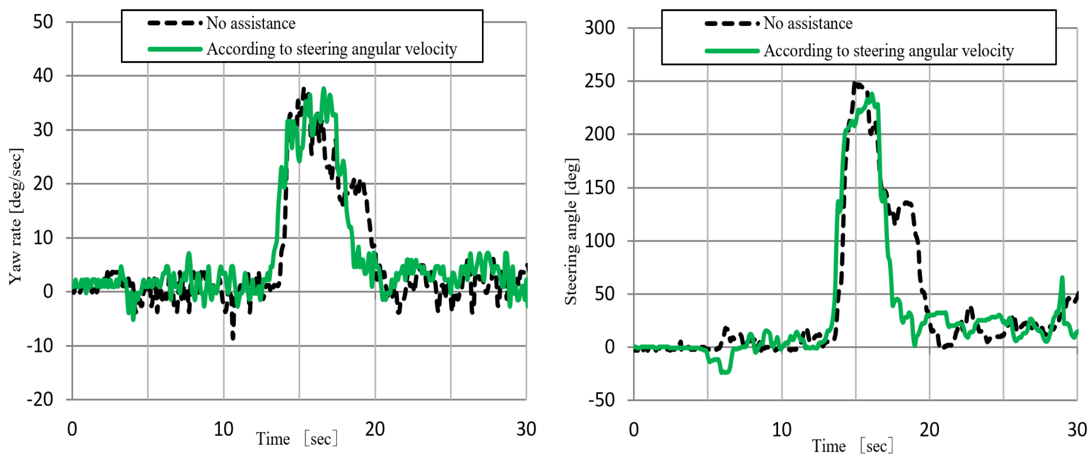
**The following subject rating value was made:1,poor; 2,fair; 3,average; 4,good; 5,excellent.



(a) (b)

Figure 11. Comparison between steering angle proportional control and no assistance during J-turn driving (a) yaw rate and (b) steering angle.

Figure 12 shows the yaw rate and steering angle of steering angular velocity control and the J-turn experiment without control. As can be seen in Figure 12(b), when comparing the yaw rate of steering angular velocity control and without control, the yaw rate of steering angular velocity control is the most stable from about 25 deg/sec to about 37 deg/sec from the peak to exit convergence. It can also be confirmed that the rise and convergence at the entrance and exit of a turn have become faster. This indicates that the control worked in a situation where a sudden steering operation is required and that stable running became possible during the turn. Comparing the steering angles seen in Figure 12(b), it can be said that the cornering limit has been improved because the steering angular velocity control is substantially unchanged and the maximum steering angle is almost the same, but the correction rudder effect is smaller than that without control.



(a) (b)

Figure 12. Comparison between Steering angular velocity control and no assistance during J-turn driving (a) yaw rate and (b) steering angle

Figure 13 shows the yaw rate and steering angle of the J-turn test results for steering angle proportional control and steering angular velocity control. Comparing the yaw rates of J-turn travel for steering angle proportional control and steering angular velocity control, Figure 13(a) shows that the steering angle proportional control reached a maximum of 52 deg/sec during a turn, whereas the maximum turning angle is 37 deg/sec in steering angular velocity control. It can also be confirmed that the inclination of the yaw rate is larger in the case of steering angle proportional control than in the steering angular velocity control. From these results, it can be said that the steering angle proportional control quickens the rise at the initial stage of turning and improves convergence, which results in improved turning stability.

Comparing the steering angles seen in Figure 13(b), it can be confirmed that the steering angle proportional control is lower than the steering angular velocity control in terms of the maximum steering angle during a turn. From the J-turn results, we find that vehicle responsiveness was improved by steering angle proportional control and steering angular velocity inner and outer wheels driving force control, thereby resulting in improved steering stability. In the case of J-turn travel, the responsiveness improved by the transient assistance of steering angular velocity control for transient movement at the initial turning stage of a turn, but the yaw rate is higher in steering angle proportional control where control also works during a turn. The corner turning ability also improved.

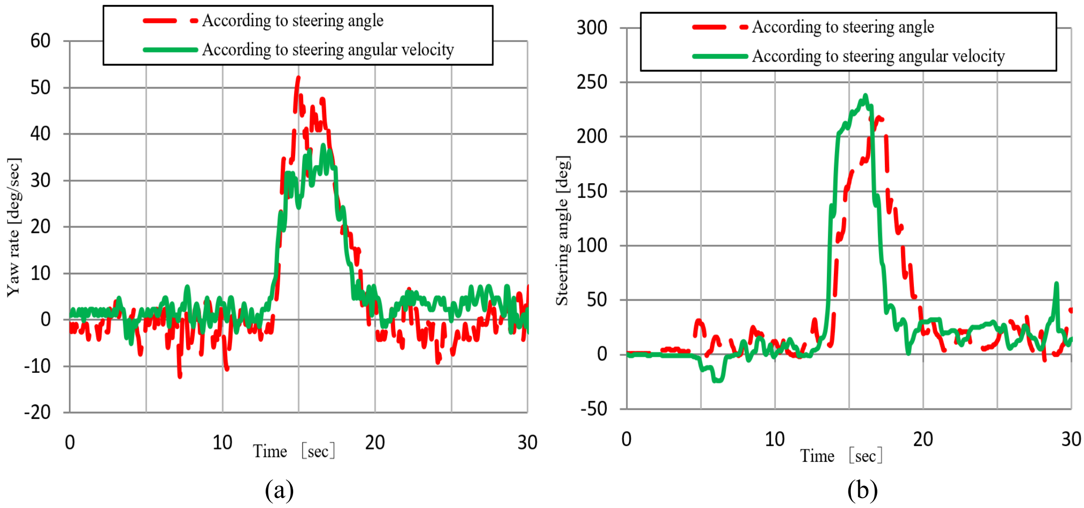


Figure 13. Comparison between steering angle proportional control and Steering angular velocity control during J-turn driving (a) yaw rate (b) steering angle

CONCLUSION

In this study, we examined and mounted an inner and outer wheel driving force control system that uses two different control methods; steering angle proportion control and steering angular velocity control to facilitate steering in turns and grasped its effectiveness via pylon slalom and J-turn tests. From the figure and the feeling evaluation of the driver in the pylon slalom test, a yaw rate increase and a decrease in the maximum steering angle about 45 deg were confirmed at the initial stage of a turn when the inner and outer wheel driving force control system used. These resulted in improved responsiveness to driver steering inputs. Additionally, in the case of the pylon slalom test, since numerous steering operations are required, we found that the steering angular velocity control method could advance the steering phase more than the steering angle proportional control method, and was more effective. In the J-turn experiment, it was confirmed that the yaw rate increased at the initial stage of the turn and the yaw rate stability during the turn improved vehicle responsiveness and steering stability. This is due to the decrease of the maximum steering angle about 40 deg, thereby allowing us to confirm the effectiveness of force control. In the case of the J-turn test, responsiveness was improved due to the transient assistance of steering angular velocity control method at the initial stage of a turn but resulted in a larger yaw rate than when steering angle proportional control method was used, even though the turning ability at the corner improved. Based on the above results, this study confirmed that the use of the inner and outer wheel drive force control could improve emergency avoidance at medium and low speeds, and thus improve both vehicle responsiveness and steering stability.

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