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Development of Integrated Dynamics Control System of SUV Vehicle with Front and Rear Steering System

Jeonghoon Song[*,#]

[*]School of Mechatronics Engineering, Tongmyong University

SUV 차량의 전륜 및 후륜 조향 장치를 이용한 통합운동제어시스템 설계

송정훈[*,#]

[*]동명대학교 메카트로닉스공학부

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ABSTRACT

In order to improve stability and controllability of SUV vehicle, Integrated Dynamics Control system with Steering system (IDCS) was developed. Eight degree of freedom vehicle model and front and rear steering system model were used to design IDCS system. It also employs Fuzzy logic control method to design integrate control system. The performance of IDCS was evaluated with two road conditions and several driving conditions. The result shows that SUV vehicle with IDCS tracked the reference yaw rate under all tested conditions. IDCS reduced the body slip angle also. It represents IDCS improves vehicle stability and steerability.

Key Words : IDCS (Integrated Dynamics Control system with Steering, 조향장치를 이용한 통합운동제어장치), FLC (Fuzzy Logic Control, 퍼지논리제어), Yaw Rate (요 속도), Side Slip Angle (횡방향 미끄러짐 각)

1. Introduction

The electronic control technology introduced into the development of the automobile during the late 1980s led to the technological development of vehicle chassis system control. Initial chassis control technology was primarily aimed at controlling only one of the chassis components. Examples are ABS (Anti-lock Brake System) or DYC (Direct Yaw moment Control) to control the brake system and AFS (Active Front wheel Steering) or ARS (Active Rear wheel Steering) to control the steering system [1,2]. In addition, the MR (Magneto-Rheological) damper used to control the suspension system is a representative one [3].

As the relevant technology developed, techniques to simultaneously control two or more components were realized. The most common form among such techniques is the integrated control of steering and braking systems. Because the adhesion limit between the tire and the road surface can be extended if the

Corresponding Author : jhsong@tu.ac.kr
Tel: +82-51-629-1537, Fax: +82-51-629-1559

braking system is included in the integrated control system, vehicle stability can be secured under a wider range of driving conditions. Excessive involvement of the control system, however, can degrade the ride comfort and fuel efficiency.

Therefore, the present study proposes an Integrated Dynamics Control with Steering system (IDCS). An IDCS is an integrated system of AFS and ARS. Since the adhesion limit between the tire and the road surface can be extended if the integrated control system consists of only the steering system, stability will be improved, and because it is a four-wheel steering system, steering performance will also be improved. It also has the advantage of improving driving convenience because the turning radius can be changed according to driving conditions [4].

Since the year 2000, various attempts have been made to improve vehicle stability and steerability by using integrated control. Song developed an integrated control system using fuzzy control[2,5]. It was for passenger cars, and the mathematical models of the AFS and ARS are considered too simple. Li and Fan also proposed an integrated control system that controls front steering and braking systems using a fuzzy control method [6].

The present study was conducted as follows for the development and performance evaluations of the IDCS. First, a nonlinear vehicle model with eight degrees of freedom was used, and mathematical models of the front and rear wheel steering systems were developed. An IDCS was developed using fuzzy control for the integrated control of the front and rear wheel steering systems. Lastly, the performance of the vehicle and IDCS was evaluated under various driving conditions.

2. Vehicle and steering system models

The present paper predicted and analyzed vehicle

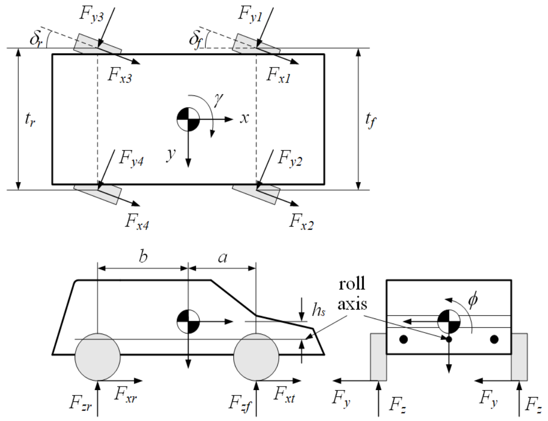

Fig. 1 Sports utility vehicle model

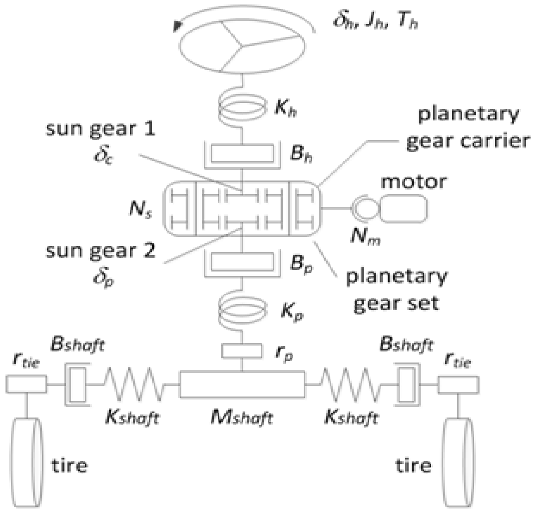

Fig. 2 Steering system model

movement using a nonlinear SUV vehicle model with eight degrees of freedom (Fig. 1). Refer to references 2 and 5 for further details of the model.

The steering system consisted of AFS and ARS. The model of the AFS system is shown in Fig. 2and it can be divided into four parts. First, from steering wheel to planetary gear set [2] is expressed as

$$J_h\ddot{\delta}_c + B_h(\dot{\delta}_c - \dot{\delta}_h) + K_h(\delta_c - \delta_h) = T_h \tag{1}$$

From planetary gear set to pinion can be expressed by the following equation:

$$J_p\ddot{\delta}_p + B_p\left(\dot{\delta}_p - \frac{\dot{\delta}_c}{N_s}\right) + K_p\left(\delta_p - \frac{\delta_h}{N_s}\right) = T_g \qquad (2)$$

The rotational motion of the steering axis is converted into linear motion by the rack and tie rod. Accordingly, it can be expressed as

$$\begin{aligned} &M_{shaftF}\ddot{x}_{shaftF} + B_{shaftF}\left(\dot{x}_{shaftF} - \dot{\delta}_p \times r_{pF}\right) \\ &+ K_{shaftF}\left(x_{shaftF} - \delta_p \times r_{pF}\right) = F_{rF} \end{aligned} \qquad (3)$$

Finally, the tire motion about the z axis is given as follows:

$$\begin{aligned} &J_{tire}\ddot{\delta}_{tire} + B_{tire}\left(\dot{\delta}_{tire} - \frac{\dot{x}_{tire}}{r_{tie}}\right) + K_{tire}\left(\delta_{tire} - \frac{x_{tire}}{r_{tie}}\right) \\ &= -T_{ext} = -F_{ext}r_{tie} \end{aligned} \qquad (4)$$

The longitudinal and lateral forces produced in the tire are transmitted to the rack, and it can be obtained as follows [2]:

$$F_{ext} = F_t \times \sin\delta_{tire} + F_s \times \cos\delta_{tire} \qquad (5)$$

The ARS has a similar structure to SBW (Steer By Wire). Rear wheel steering angle is determined by the IDCS system, and a single motor attached to the pinion gear determines the rear wheel steering angle. The model equation of the ARS system can be expressed as follows [2]:

$$\begin{aligned} &M_{shaftR}\ddot{x}_{shaftR} + B_{shaftR}\left(\dot{x}_{shaftR} - \dot{\delta}_{mR} \times r_{pR}\right) \\ &+ K_{shaftR}\left(x_{shaftR} - \delta_m \times r_{pR}\right) = F_{rR} \end{aligned} \qquad (6)$$

3. IDCS controller

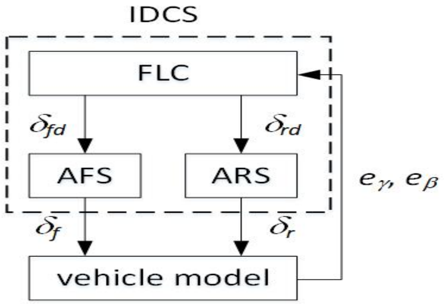

Fig. 3 Structure of IDCS system

Table 1 Fuzzy rules

e_γ	e_β	δ_{fd}	δ_{rd}	e_γ	e_β	δ_{fd}	δ_{rd}
NB	PB	NVB	PVB	ZE	NS	ZE	NS
NB	PM	NVB	PB	ZE	NM	PS	NM
NB	PS	NB	PB	ZE	NB	PS	NB
NB	ZE	NB	PM	PS	PB	ZE	NS
NB	NS	NM	PM	PS	PM	PS	NS
NB	NM	NM	PS	PS	PS	PS	NM
NB	NB	NS	PS	PS	ZE	PM	NM
NM	PB	NVB	PVB	PS	NS	PM	NB
NM	PM	NB	PB	PS	NM	PB	NB
NM	PS	NM	PB	PS	NB	PB	NVB
NM	ZE	NM	PM	PM	PB	ZE	NS
NM	NS	NS	PM	PM	PM	ZE	NS
NM	NM	ZE	PS	PM	PS	PS	NM
NM	NB	ZE	PS	PM	ZE	PM	NM
NS	PB	NB	PVB	PM	NS	PM	NB
NS	PM	NB	PB	PM	NM	PB	NB
NS	PS	NM	PB	PM	NB	PVB	NVB
NS	ZE	NM	PM	PB	PB	PS	NS
NS	NS	NS	PM	PB	PM	PM	NS
NS	NM	NS	PS	PB	PS	PM	NM
NS	NB	ZE	PS	PB	ZE	PB	NM
ZE	PB	NM	PB	PB	NS	PB	NB
ZE	PM	NS	PM	PB	NM	PVB	NB
ZE	PS	ZE	PS	PB	NB	PVB	NVB
ZE	ZE	ZE	ZE				

Table 2 Linguistic terms

NVB	Negative Very Big	PS	Positive Small
NB	Negative Big	PM	Positive Medium
NM	Negative Medium	PB	Positive Big
NS	Negative Small	PVB	Positive Very Big
ZE	Zero Equal		

The IDCS controller is a system developed for an active and simultaneous integrated control of the front and rear wheel steering angles. The IDCS has a double-layer structure for proper integrated control (Fig. 3). The first layer uses FLC (Fuzzy Logic Control) and calculates the target front and rear steering angles (δ_{fd}, δ_{rd}) [7]. The fuzzy input and output consisted of 7−9 triangular fuzzy membership functions, and Mamdani fuzzy-inference model was used [8]. Table 1 shows the fuzzy rule, and Table 2 shows the meanings of NVB, NB, NM, NS, ZE, PS, PM, PB, and PVB used in Table 1. The fuzzy rule in Table 1 was set up based on the experience and many trials and errors of the author.

The second layer was to actually implement the calculated target steering angles using AFS and ARS (δ_f, δ_d). Using a PID control technique, the steering motor was controlled so that the actual steering angle accurately follows the target steering angle. Inputs to IDCS were yaw rate error (e_γ) and lateral slip angle error (e_β). Errors are defined as follows:

$$e_\gamma = \text{yaw rate - reference yaw rate}$$

$$e_\beta = \text{body slip angle - reference body slip angle}$$

4. Results

Vehicle responses were examined under various driving and input conditions to evaluate the performance of the IDCS developed in the present study. The friction coefficient between the tire and the road surface was calculated using the Burckhardt formula [9].

4.1 Sinusoidal steering input applied

First, vehicle responses were examined with a sine wave steering input applied with the SUV running at 25 m/s on a dry asphalt surface. Fig. 5(a) shows steering input by the driver while Fig. 5(b) shows the front and rear steering angles of a vehicle equipped with the IDCS. The figures show that as the steering input by the driver increases, the front and rear steering angles of the IDCS also gradually increase. Figs. 5(c) to 5(f) show yaw rate, lateral slip angle, roll angle, and lateral acceleration, respectively. A close examination of the figure shows that IDCS does not significantly improve vehicle performance on a dry asphalt surface.

Fig. 6 shows the response of the SUV running at 20 m/s on a snowy road when a sinusoidal steering input is applied. A vehicle equipped with the IDCS showed a stable response even if the steering angle increases. On the other hand, the response of the vehicle without an IDCS becomes unstable as the steering input increases. Especially, as shown in Fig. 6(c) and Fig. 6(f), if the yaw rate and lateral acceleration of the SUV exceed the adhesion limit, the vehicle does not respond to the steering input and becomes unsteerable.

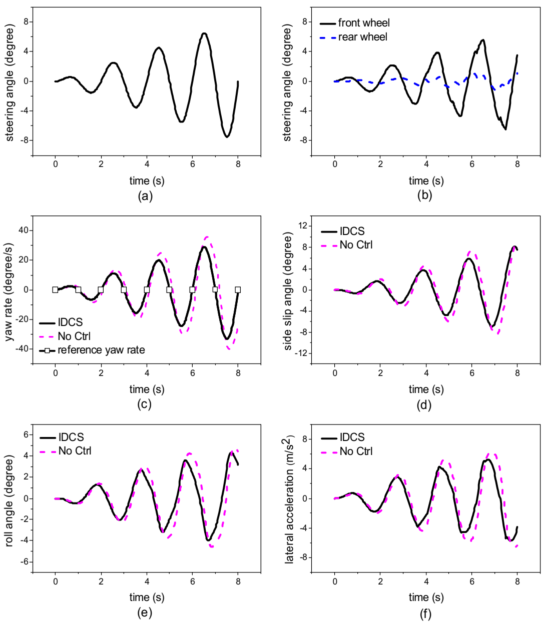

Fig. 5 Responses of IDCS and SUV vehicle on dry asphalt road with sinusoidal steering input

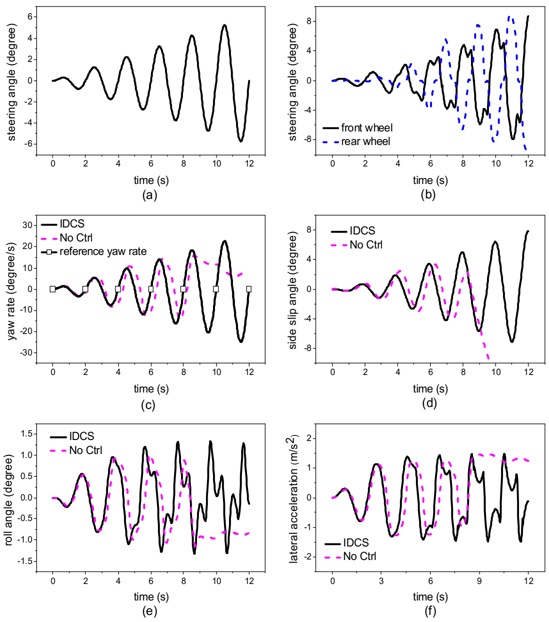

Fig. 6 Responses of IDCS and SUV vehicle on snow covered road with sinusoidal steering input

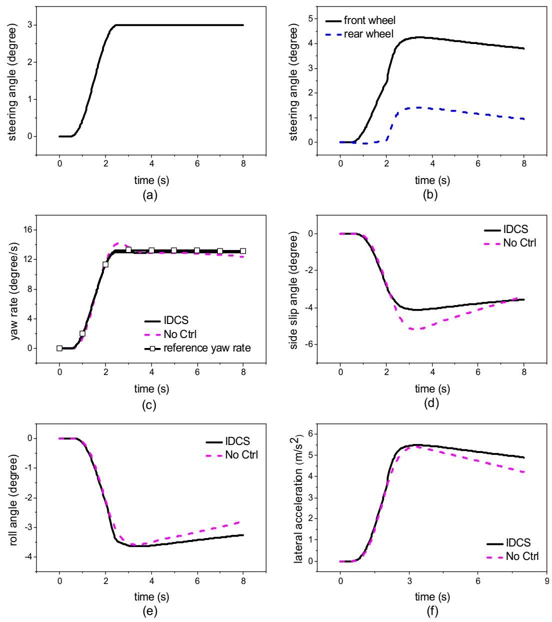

Fig. 7 Responses of IDCS and SUV vehicle on dry asphalt road with step steering input

4.2 Step waveform steering input applied

Next, the responses of IDCS and SUV were examined when a step waveform steering input was applied. Fig. 7 shows the responses of the controller and the vehicle with a step steering input applied with the vehicle running at 25m/s on a dry asphalt surface. Fig. 7(a) shows the steering input of the driver and Fig. 7(b) shows the output of the IDCS. As shown in the figure, the vehicle without an IDCS displays larger response changes than the vehicle equipped with an IDCS to the same steering input. This means that the driving performance of the vehicle is unstable.

Fig. 8 shows the responses of the controller and vehicle when the vehicle is running at 10m/s on a snowy road and the steering input shown in Fig. 8(a) is applied. Under the given driving conditions, the IDCS generated minimal rear wheel steering angle but somewhat large front wheel steering angle. This appears to be an effort to minimize the lateral

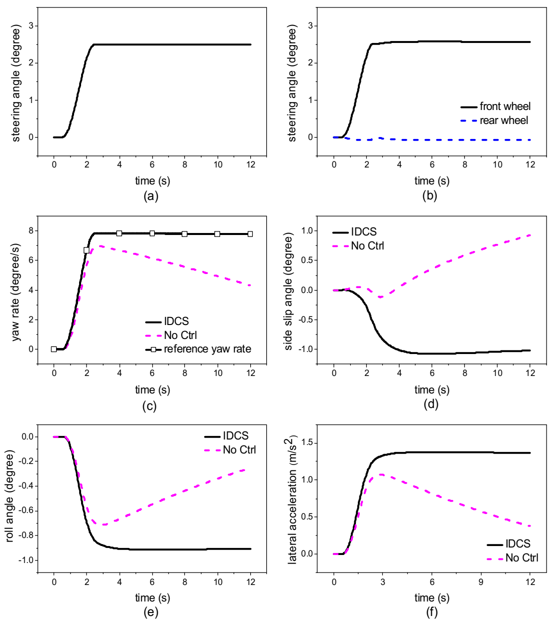

Fig. 8 Responses of IDCS and SUV vehicle on snow covered road with step steering input

slip of the vehicle. On the other hand, the yaw rate, roll angle, and lateral acceleration of a vehicle equipped with IDCS responded very well to the steering input, as shown in Fig. 8(c), (e), and (f). The results mean that an SUV equipped with an IDCS is steerable on a slippery road surface and the vehicle is running stably. On the contrary, an SUV without an IDCS does not respond to the steering input.

5. Conclusion

The present study was conducted to develop and evaluate the performance of the proposed IDCS, which is an integrated AFS/ARS system. For the present study, a vehicle with eight degrees of freedom was used and the integrated control of AFS and ARS was performed using fuzzy logic control.

Performance evaluation showed that the yaw rate of the vehicle equipped with the IDCS was following the target yaw rate well under most driving and road conditions and demonstrated more stability and steerable performance improvement compared to the vehicle without an IDCS. The performance improvement of the SUV by the installation of the IDCS was greater when the road surface was more slippery.

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Appendix - Nomenclature

a/b : distance from COG to the front/rear wheel =

1.23 m / 1.535 m

$B_h/B_p/B_{tire}$: torsional damping coefficient of hand wheel/pinion/tire, kg m^2/s

B_{shaft} : damping coefficient of rack and tie rod, kg/s

C_f/C_r : cornering stiffness of front/rear axle, N/rad

C_{af}/C_{ar} : cornering stiffness of front/rear tire, N/rad

F_t/F_s : longitudinal/lateral tire force, N

F_x : tire force, N

h_s : distance from sprung mass CG to roll axis = 0.3m

I_z : vehicle moment of inertia about z axis = 1627kg m^2

$J_h/J_p/J_{tire}$: rotational inertia moment of hand wheel/ pinion/tire, kg m^2

$K_h/K_p/K_{tire}$: torsional stiffness of hand wheel/pinion/ tire, kg m^2/s^2

K_{shaft} : stiffness of tie rod, kg/s^2

M_{shaft} : mass of rack and tie rod, kg

N_m : gear ratio between steering wheel and assistant motor

N_s : ratio between steering wheel angle and pinion angle

r_{pF}/r_{pR} : radius of front/rear pinion = 0.074m

r_{tie} : distance between tie and center of tire, m

t_f, t_r: front and rear wheel distance = 1.638m

T_g : output torque from planary gear set, Nm

T_h : input torque from driver, Nm

v_x : longitudinal velocity, m/s

v_y : lateral velocity, m/s

β : body side slip angle, rad

$\delta_h/\delta_c/\delta_p/\delta_{tire}/\delta_{mR}$: hand wheel/sun gear/pinion/tire /rear motor angle, rad

γ : yaw angle, rad

ϕ : roll angle, rad